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Technical liaisons in engineering design: Understanding by modelling

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TECHNICAL LIAISONS IN ENGINEERING DESIGN: UNDERSTANDING BY MODELLING

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Abstract

This thesis considers the integration of suppliers and particularly their information into the engineering design process. The need for empirical research within this area has arisen owing to recent changes in engineering design practice.

The research has been undertaken from two interrelated perspectives. The first was focused on the organisation and handling of standard supplier literature; an information source that was shown to be widely used and heavily relied upon within the design and development of new products. The second was focused on modelling information flows and interactions within and between the design functions of customers and suppliers engaged directly in product development.

The latter perspective, that was undertaken in order to facilitate a better understanding of supplier information integration, has been the primary focus of this research. The lack of attention that this area has received, however, was reflected by a lack of suitable modelling techniques to study the engineering design process from an information utilisation and exchange standpoint. This research has therefore resulted in a new software based information modelling technique, termed the Product Information Modelling System (PIMS). PIMS was installed within a number of organisations where it was used by engineering designers to collect and simultaneously model case study data.

The research has provided insights into an area of design that was not well understood previously. It has both identified deficiencies in current practices and proposed ways by which they may be overcome. Finally, it has provided a platform for future work and vital understanding within this new and complex area.

Acknowledgements

For the past three years I have had the privilege of being able to peruse knowledge within an area in which I have become so fond. It has been a most rewarding experience, both in terms of what I have learnt and who I have met. For this I am indebted to many people and organisations.

I owe a great deal to Steve Culley and Chris McMahon, who introduced me to research and guided me on my voyage of discovery. Their countless discussions and technical input has been invaluable, particularly in the context of proof-reading this thesis. My appreciation also extends to the Engineering and Physical Sciences Research Council from which the research work was funded*.

Numerous others have contributed, either directly or indirectly, to the successful completion of this work. I would like to acknowledge Andy Sales, Tony Chambers, Mike Vernon, Tim Gamsten, Tim MacLean, James Smith, Steve Smith, Paul Fisher, and Paul Bowden; engineers who devoted considerable time and effort during the collection of much of the detailed case study data. I would also like to thank all those who aided in the distribution of the questionnaire, and especially those who took the time to fill it in and return it. My gratitude also extends to those who aided in the development and testing of PIMS.

To date I have spent almost a third of my life at Bath University and I will look back on it with very fond memories. I am indebted to my fellow students and to all my friends who have made *Bath Life* such a pleasant experience, especially the Wasp and the Troll. Finally, I would like to thank my family whose sacrifices over the years have ensured a sound education and up-bringing. Their support has been instrumental in my achievements thus far.

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Glossary

CE	-	Concurrent Engineering
CAD	-	Computer Aided Design
CAM	-	Computer Aided Manufacture
DFD	-	Data Flow Diagram
DTI	-	Department of Trade and Industry
EDI	-	Electronic Data Interchange
ICAM	-	Integrated Computer Aided Manufacturing
IDEF	-	ICAM Definition
IED	-	Institution of Engineering Designers
IGES	-	International Graphics Exchange Specification
IT	-	Information Technology
MDI	-	Multiple Document Interface
MIM	-	Multi-functional Information Model
OEM	-	Original Equipment Manufacturer
PDS	-	Product Design Specification
PIMS	-	Product Information Modelling System
RAD	-	Role Activity Diagram
SIC	-	Standard Industrial Classification
STEP	-	Standard for the Exchange of Product data
UK	-	United Kingdom

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Chapter 1. Introduction

Engineering design has been described as a practice, mediated by scientific and engineering knowledge, aimed at transforming a set of needs into an artefact (Konda *et al*, [1992]). It has a marked impact upon an artefact's cost, quality, reliability, performance, and time to market; factors that clearly need to be optimised in order to accrue competitive advantage in today's aggressive global marketplace (Womack *et al*, [1990]).

In recent years engineering design has thus been the subject of much attention and change. The following sections will provide an overview of the more significant of these changes with a view to establish their impact, both in terms of success and failure. Key research issues will therefore be identified and those that are to be addressed by this research will be highlighted.

1.1 Supplier Integration

Organisations, in an attempt to survive in the current industrial climate, have been forced to integrate a wide range of (innovative) technologies into the product engineering design and development processes (Ebert *et al*, [1986]). Owing to the high degree of specialisation, however, it has become almost impossible for them to do this on their own, and they have therefore tended to concentrate on their own core specialisms and to delegate the remainder out to suppliers[1] (Simons, [1994]; Wijnstra and Stekelenborg, [1996]).

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[1] Ward *et al* [1995], for example, have cited cases of major Japanese automakers outsourcing over 70% of their vehicle content to suppliers.

The role of suppliers has therefore evolved; they are no longer relied upon solely for the provision of standard components and subcontracted manufacture. Rather, they are having to provide design experience for their own product's application to the overall design of the product (Vonderembse and White, [1991]; PA Consultants, [1989]).

Organisations are thus becoming increasingly reliant upon suppliers for the provision of information throughout the engineering design process, and this in turn has brought about a number of new challenges for individuals and organisations alike. For example, new procedures and mechanisms may be required simply to facilitate the selection of suppliers, as organisations may need to take account of the information available from suppliers within their assessment schemes; a point that is exemplified by Martin [1989], who states that "... *increasingly it is information that makes the difference between a marginal supplier and a good one...*". More significantly, though, organisations and, in particular, engineering designers are faced with the challenge of integrating the information and knowledge available from suppliers into the engineering design process; a distinct problem owing to the changes, as outlined below, in the way that engineering design is practised, the lack of tools to support this process, and, more significantly, the lack of guidelines, techniques, or procedures, pertaining to how this may be achieved.

1.2 Concurrent Engineering

The traditional approach of managing engineering design-and-manufacture end-to-end, and in almost total isolation, often resulted in designs that were costly, time consuming, or even impossible, to manufacture, assemble, package, etc.. Pressures (in the early 1980's) to reduce product development times and to produce products that were better suited to the customers' needs led to this sequential approach being superseded by a parallel one, known as simultaneous or Concurrent Engineering (CE) (Carter and Baker, [1992]); a practice cited as being the key to successful new product development (Nevins and Whitney, [1989]).

A central issue in the adoption of CE is the organisation of the design process to enable early and multi-criteria considerations of a wide variety of issues (Finger and Dixon, [1989]). Attempts to achieve this have been made by arranging for all those who can bring expertise to bear on an emerging design to collaborate concurrently. This is an inherently difficult activity, particularly when external parties such as suppliers are involved, as a large part of the expertise in engineering is distributed throughout design and manufacturing functions (Bond and Ricci, [1992]). Further, simply 'bringing together' these experts is only one aspect of CE, it requires, for example, the transfer of the right quantity of information to the right individuals at the right time (Christian and Seering, [1995]). Moreover, in each phase of the product development process engineering designers often have to work with less detailed or partial information, and this has to be transferred quickly between all team members in order to provide feedback on how well the design is meeting the overall needs.

It is thus clear that in order to successfully implement CE organisations need to undertake, for example, cultural, organisational, and procedural changes. These changes are necessary and a prerequisite to exploiting benefits from many of the computer-based tools intended to support the CE design process (Konsynski and Warbelow, [1989]; Schrijver and Graaf, [1996]). Prior to making such changes, however, a thorough understanding of current practices is required in order to both assess where they need to be made and to enable a tangible evaluation of their impact (Eppinger *et al*, [1990]). Conversely, though, studies of the engineering design process, and in particular the CE design process, have been rather limited. Further, Rangan and Fulton, [1991] have noted that "*Few studies have addressed the engineering design process from an information exchange standpoint*", and as a consequence current practices are not well understood (Ebert *et al*, [1986]; Schrijver and Graaf, [1996]). Overcoming this deficiency is not only essential for the successful implementation of CE (Fox, [1994]) but, as noted by Baya and Leifer, [1995], it may also result in improvements in the efficiency of the design process and the development of new methods and tools to enable it to be better supported.

1.3 Support Tools

A recent survey undertaken by Boston *et al* [1998a] revealed that over 95% of engineering designers have access to a personal computer. It now plays an integral role within the design process; computer-based tools and systems not only provide key support mechanisms for CE (McLeod, [1991]) but they have been cited as the main driving force in design today (Whitney, [1990]). They have, for example, enabled engineering designers to:

- Produce results that were not previously attainable with manual methods (McMahon and Brown, [1993]).
- Locate, retrieve, and re-use data, in a more efficient and effective manner (Pye, [1991]).
- Transfer data rapidly between different users and departments (Angus and Murdoch, [1993]).

Further, Pye [1991] has noted that the use of such systems and tools, that include, for example, Computer Aided Design (CAD) (Medland, [1986]), Finite Element Analysis (Fagan, [1992]), Knowledge-Based Engineering systems (Anderson, [1994]), and Computational Fluid Dynamics (Anderson, [1995]), has helped to minimise design errors, to reduce product development costs (by an estimated 10 %), and to reduce the time taken to get a product to market (by an estimated 30%).

Having consulted the research literature, however, it is considered that the above benefits may represent only a limited proportion of those that that could potentially accrue from the exploitation of today's computing technology. This view is based on the following assertions:

- The majority of effort in this area has been focused around the development of tools and languages to enable the representation, manipulation, and transfer of what is called information, but in reality is often data[2]. Conversely, however,

[2] The destination between information and data is discussed in Section 4.2.

there are a lack off tools to aid the communication, co-ordination, and acquisition of information; activities that, as noted in Section 1.4, consume a large proportion of the engineering designers' time (Toye *et al*, [1994]).

- Use of the vast majority of existing tools is often confined to the later stages of the engineering design process[3], and hence aids for the engineering designer in the early stages, where most benefits could be accrued[4], are limited (Cartmell *et al*, [1993]; Baya and Leiffer, [1995]; Lawrence, [1990]).

1.4 Information Issues

From the previous discussions it is apparent that many of the outstanding research issues pertain to information; it is considered that this may be owing to a number of factors, for example:

- Information is an all too familiar and yet intangible enterprise asset that is difficult to quantify or even place a value upon (Benyon, [1990]). Information based research, therefore, is not only difficult but it is often overlooked.

- The amount of information available is increasing about 2.5 times as fast as world's population (Ehrlenspiel, [1997]). In turn, therefore, its management is becoming increasingly significant.

- Information plays a vital role within the engineering design process. This point is most appropriately emphasised by the following definition (Eder, [1989]):
  - "*Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted to information in the form of descriptions of technical systems, such that these technical systems meet the needs of mankind.*"

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[3] Those exceptions that do exist tend to be knowledge-based and have limited generic capabilities, such as the sub-assembly design tool developed by Theobald *et al* [1993].

[4] Overall product quality and the vast majority of product costs are built in within the early phases of the design process (Section 2.3.2).

It is considered, however, that the above definition fails to emphasise a number key aspects of engineering design. Further, those aspects that it does emphasise appear to have received significant attention, whereas those key aspects that it does not emphasise appear to have received insufficient attention. For example:

- It only considers that engineering design involves the manipulation and representation of information.
  - Support of these two aspects has been the primary focus of 'design information management' research (Majumder and Fulton, [1990]); a point that was emphasised in the context of support tools (Section 1.3).

- It fails to emphasise the communication and co-ordination of information.
  - These aspects, that have been noted to consume up to approximately two thirds of an engineering designer's time in collaborative design projects (Fox, [1994]), were shown within Section 1.2 to be vital constituents in the realisation of CE (Angus and Murdoch, [1993]). Conversely, though, it was noted that these aspects are not well understood, and, of further significance, they tend to be ill supported (Eastman, [1997]).

- It fails to emphasise the acquisition of information.
  - This aspect, that has been noted to consume around one quarter of an engineering designer's time (Rzevski, [1985]; Cave and Noble, [1986]; Putre, [1991]; Yeaple, [1992]; Court *et al*, [1993]), is an integral part of the engineering design process (Ennis and Gyeszly, [1991]). Moreover, it is considered to be a key constituent in successful new product development, and yet, as discussed below, it appears to have received insufficient attention.

Apart from the changes that have recently taken place in the way that engineering design is practised, engineering designers need access to information, where this may include, for example, previous design schemes, standard component catalogues, trade magazines, design guides, or patents (Court *et al*, [1993]). If they cannot access this information, cannot re-apply it, or if it is not accurate or current innovation may be constrained (CIS, [1996]), or worse still they may make mistakes or misjudgements on aspects of the product's design (Rangan and Fulton, [1991]).

The issues surrounding information access therefore should have received significant attention; especially in view of the increasing volumes of information, the pressures to access information in a timely manner, the pressures to design quality products that incorporate diverse technologies, etc.. Reference to the research literature, however, suggests that this is not the case. For example, Workman [1995] has noted that engineering designers frequently find it difficult to stay abreast of what is technically feasible and Fox [1994] has noted that engineering designers are often unable to access information, even when they know it exists!

1.5 Further Research Issues

The previous sections have provided an insight into the pressures facing today's engineering organisations and given a broad overview of the recent changes that have taken place in the way that engineering design is practised. Within this, a number of key research issues were identified. The most significant of these, however, is considered to be the need to better understand, from an information exchange standpoint, how engineering design is practised when external parties such as suppliers are involved. This need is especially evident in view of the fact that organisations will, as time goes by, place increasing demands upon suppliers for information, knowledge, and services (Pollmann, [1993]). Conversely, though, it is apparent that the fulfilment of this need is currently frustrated by a lack of tools to enable the engineering design process to be analysed and subsequently understood from an information exchange standpoint.

The engineering design process is the subject of many complex communications[5] and interactions, that may vary from design project to design project. Owing to

[5] For example, information may be obtained or exchanged via a wide variety of media, it may undergo changes in content, format, presentation, etc., and it may come from or be passed on to a multitude of sources or recipients that may even be external to the organisation.

cognitive limitations, therefore, these complexities need to be managed in order for it to be well understood. Reference to the research literature has indicated that this could be achieved via the use of information or process models, that provide a simplified view of the 'world of interest ' (Martin, [1989]; Chadha *et al*, [1991]). Conversely, however, it has been noted that the formal techniques used to construct these models are not ideally suited to engineering information or its handling within the design process[6] (Rabins *et al*, [1986]; Rangan and Fulton, [1991]; Court *et al*, [1996]; Boston *et al*, [1997a]).

It is clear, therefore, that there is a pressing need to overcome this modelling deficiency, and this in itself is considered to be a key research issue; a viewpoint that has been stressed by a number of researchers and, more significantly, research institutions. For example, the Department of Trade and Industry, who also emphasised the importance of customer-supplier relationships and information integration, have expressed the need for a methodology with which to define data flows and associated activities (PA Consultants, [1989]). More recently, however, the National Science Foundation stated, in a report to the design community (NSF, [1996]), that:

> "*Companies need a better understanding of their product design process. Enhancements in the design organization and process infrastructure are needed. Tools are needed to study the design process in the context of information flow, dependencies, and concurrence*".

The above issues will be discussed further in the following section, that presents the Hypotheses and outlines the aims and objectives of this research.

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[6] Primarily, these techniques were developed for information of a static nature whereas engineering information tends to be dynamic; it may, for example, evolve or change from a verbal to a textual or even a diagrammatic format.

1.6 Research Aims

After due consideration of the literature and discussions with practising engineering designers and mangers, it was possible to develop a number of hypotheses within the area of design information and suppliers. The principal aims of this research are to investigate these hypotheses, that are presented as follows:

Hypothesis 1

- The wealth of information and knowledge available from suppliers is poorly utilised by engineering designers.

Hypothesis 2

- The utilisation and exchange of information between customers and suppliers during the product development process can be modelled.

Hypothesis 3

- These models can be usefully used in a design tool to help integrate suppliers into the engineering design process.

In order to both enable the aims of this research to be met and to address, in whole or in part, a number of the research issues that were highlighted within previous sections, the following key objectives were identified:

- Review the research that has been undertaken within the areas that are related to this research and identify any outstanding research issues that need to be addressed.

- Establish the information access related demands that engineering designers place on standard supplier literature and asses whether current systems for storing and handling this information source enable these demands to be met.

- Collect empirical data pertaining to the information flows and interactions that take place within and between the design functions of customers and suppliers engaged in product development.

- Develop information categorisations and modelling techniques that are applicable to the information flows and interactions that take place in collaborative product development.

- Integrate the information categorisations and modelling techniques into a system that is capable of enhancing the integration of the supplier into the engineering design process.

- Test and validate these techniques against design situations in an industrial context.

These objectives will be addressed within the next seven chapters of this thesis; as outlined within the following section.

1.7 Thesis Structure

This research follows two parallel lines of investigation. The first line relates to standard supplier literature and how it is organised and handled within design functions. The second line relates to modelling the information flows and interactions that take place within and between the design functions of customers and suppliers engaged in product development. The presentation of these aspects within this thesis should be apparent from the following overview:

Chapter 1 has highlighted the main trends influencing engineering design within the manufacturing industry. It has provided an overview of current research and, above all, identified a number significant gaps or flaws within it. The need to overcome these flaws, that include a poor conception of how information is currently organised and handled within design functions, a limited understanding of collaborative engineering design processes from an information exchange standpoint, and a lack of tools to facilitate this understanding, has formed the basis of the author's research, as outlined within this chapter.

Chapter 2 examines the research literature in some more detail and thus identifies further issues of relevance to this research. In particular, it focuses on the nature of engineering design, the techniques and methods that are used to study it, the current theories and methodologies pertaining to how it should be practised within the domain, the computer-based tools and systems currently available to support it, and issues related to CE and design for the life-cycle. Throughout this chapter, emphasis is placed upon the integration of supplier information into the engineering design process.

Chapter 3 presents the author's research work pertaining to standard supplier literature; the first of the parallel lines of investigation outlined above. It reviews previous research into the utilisation and management of this information source within the domain of engineering design. Subsequently, it presents and discusses the (qualitative and quantitative) findings that emanated from an in depth investigation into the way that this information source was organised and handled within an engineering concern. A number of these findings were reinvestigated and generalised, by way of a questionnaire survey, within Chapter 7.

Chapter 4 represents the start of the author's work pertaining to the second line of investigation; a theme that will be continued in Chapters 5 and 6 and part of Chapter 7. It defines information, identifies factors that impinge upon its value, and provides a review of the formal techniques used to model it. Subsequently, it evaluates these techniques against a number of criteria and reveals that they are not ideally suited to this research. Finally, it presents the protocol behind a new technique, termed the Multi-functional Information Model (MIM), that was developed by the author specifically to meet the needs of this research.

Chapter 5 presents a software based tool, termed the Product Information Modelling System (PIMS), that integrates various classification schema with an extended version of the MIM technique. It was developed in order to both enhance the capabilities of this technique and to enable a number of (highlighted) data collection problems to be overcome. This chapter provides an overview of the data entry requirements for PIMS, a walk through of the model building process using PIMS, and, within this, it also highlights a number of the salient functions and features of PIMS.

Chapter 6 is primarily concerned with the validation of PIMS in an industrial context. It outlines the methodologies that were employed in the collection of case study data, provides an overview of a number of case studies, and describes the practical application of PIMS to a particular case design project. Discussion is centred around the observations that emanated from the analysis of PIMS models that were produced as a result of this and the additional case design projects. Within this discussion an understanding of the engineering design process from an information exchange standpoint is also gained.

Chapter 7 presents and discusses the results of an extensive postal questionnaire survey of over 230 engineering designers and managers within the United Kingdom (UK). This survey was undertaken in order to both enable the further validation of a number of the findings presented within previous chapters, and in particular Chapters 3 and 6, and to enable additional research issues to be addressed. In keeping with the theme of this research, it is focused around standard supplier literature and the integration of suppliers into the engineering design process.

Chapter 8 addresses the original hypotheses of this research, discusses its limitations, and provides the overall conclusions to the work that has been undertaken and presented within this thesis. Finally, it proposes a number of future research avenues that would enable this research to be both extended and improved. Figure 1.1 shows a simplified diagram of the structure of this thesis and the research conducted by the author.

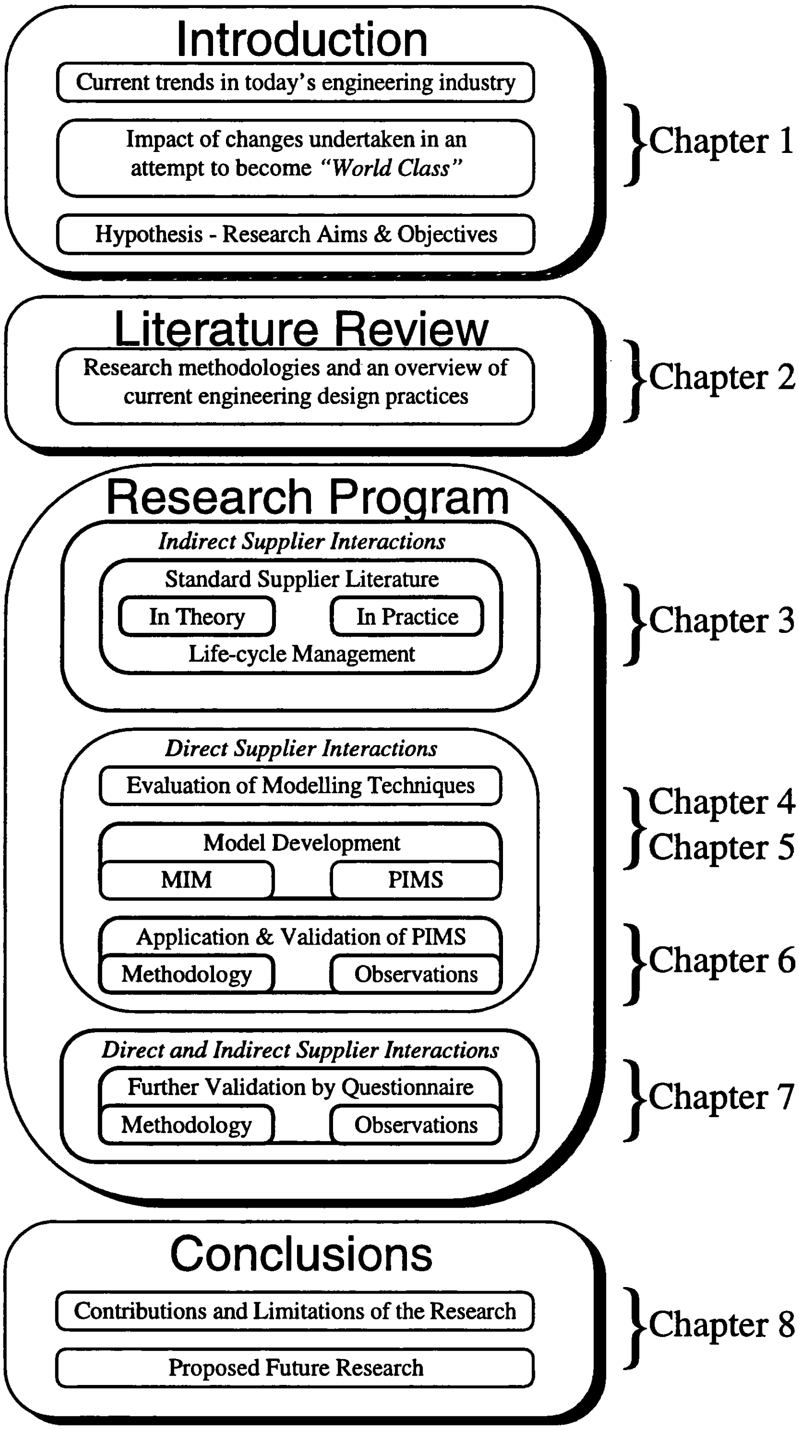

Figure 1.1: Thesis Structure

in design research; Hubka [1982], Pahl and Beitz [1984], and Cross [1985] are notable from their publications. Comprehensive reviews of the various design methodologies have been presented by Cross [1993] and Finger and Dixon [1989].

An overview of the research techniques frequently employed within the domain of engineering design, together with the major methodologies that have emanated from much of this research, are presented as follows:

1. *Research techniques in engineering design* - during attempts to understand and describe the sequences of events and interactions that occur as design is carried out in practice a multitude of research techniques have been employed. These have included, for example, protocol analysis, cognitive modelling, and case-studies of engineering designers involved in 'real' design situations.

2. *Models of design processes* - that prescribe how engineering design should be carried out in practice. These models have been based on empirical research and the intuition of their creators. Also, within the 'prescriptive' area, there exist a number of models that describe the desired attributes that a good design artefact should possess. Examples of these are provided by Suh [1990] and Taguchi [1986].

3. *Concurrent engineering* - that deals with product design in an environment where all disciplines required to bring a product to market move through the phases of the design process in a simultaneous manner. It is concerned with the organisation and control of both the design process and the information that is required and utilised within it. It is interesting to note that CE is based on previous work as it also suggests that there are phases in the design process.

4. *IT support and product representation in design* - that deals with those methods and tools that aid the engineering designer by providing information on which design evaluations and decisions may be based; accomplish specific tasks of the design process; and finally, that enable a design artefact to be fully defined.

This thesis will draw upon research from a large number of areas and in particular those highlighted above. The remainder of this chapter will therefore present aspects from the above areas of relevance to this research. Particular emphasis will be placed upon the supplier and information in engineering design. Subsequent chapters will present other areas of the research literature in the specific context of the author's research.

2.2 Research Techniques in Engineering Design

In an attempt to answer the question of how designers create designs, researchers from many fields have employed techniques from the field of the social sciences in order to study the processes, strategies, and problem solving methods that designers use (Wallace and Hales, [1989]). The following sections provide an overview of these techniques, that include protocol analysis, cognitive modelling, and case studies, highlight their inherent limitations, and discuss their applicability to this research.

2.2.1 Protocol Analysis

Protocol analysis was devised to infer the information processing mechanisms underlying human problem solving behaviour (Newell and Simon, [1972]). In the context of engineering design it has allowed researchers to study the behaviour of engineering designers in their natural setting, thus protecting the results to a certain extent against distortion by the experiment (Adelson, [1989]).

In a design protocol, the actions of a person performing a design task are recorded as the design evolves. The mechanisms used to record this behaviour can include the information created as a result of the person's actions, along with notes and possibly audio or even video recordings made by the researcher. Within the domain of engineering design, however, the verbal protocol technique appears to have been the most popular. Generally, this involves the engineering designer thinking aloud, and when information appears to be incomplete questions are asked. This technique is not without its flaws, however, as most people find it difficult to verbalise their thoughts (Blessing, [1989]; Dorst and Cross, [1995]), and to some extent it gives them a different form and significance than they would have had in a process without thinking aloud (Ehrlenspiel and Dylla, [1989]).

Aside of the above deficiencies, protocol analysis has been widely used within the domain of architectural design (Krauss and Myer, [1970]; Eastman, [1970]; Lawson, [1980]) and, more recently, mechanical engineering design (Stauffer *et al*, [1987]; Schon, [1988]; Ullman and Dietterich, [1987]; Waldron and Waldron, [1987]). Such studies, however, have largely focused on the initial phases of the design process, and while there is a consensus that designers exhibit the range of design strategies during all phases Finger and Dixon [1989] argue that this has never been proved. Furthermore, they state that few formal protocol studies have been done on design teams, and hence they have tended to ignore the interactions that form a large part of the engineering designers' day-to-day activities.

2.2.2 Cognitive Modelling

This technique is used to describe the processes that underline the set of behaviours that constitute a skill, via mechanisms with defined functionality that can describe a process that transforms classes of input to classes of output, along with the interactions between the mechanisms (Finger and Dixon, [1989]). Since these models describe the cognitive system at a functional level, they act as ideal platforms for building computer-based models that describe, simulate, or emulate the skills that humans employ in solving problems. Thus, they have the potential to facilitate the development of systems based on human design processes. The wealth of knowledge on this topic appears to be minimal, however, and hence the following represents the majority of published research related to this field: Adelson [1989]; Gero and Coyne [1985]; and Perlman [1989]. This technique will not be pursued in this research.

2.2.3 Case Studies

The case study method has been used extensively in the course of engineering design research (Bessant and McMahon, [1979]; Black and Shaw, [1991]; Bucciarelli, [1988]; Ebert *et al*, [1986]; Fulmer *et al*, [1990]; Hales, [1987]; Lera, [1981]; Lera *et* *al*, [1984]; Marples, [1961]; Turner, [1977]). It can, and frequently does, employ a multitude of techniques for gathering data. For example, it may employ retrospective techniques, such as interviews, questionnaires, and the retrospective technique, and it may employ 'real time' techniques, such as direct observation, participant observation, and involved observation. Each of these techniques have their advantages and disadvantages; an overview of these is presented as follows:

- *Retrospective* - data collected retrospectively are susceptible to distortion owing to time, and may include what the engineer perceived happened, which is not always what actually happened (Stauffer and Ullman, [1988]; Blessing, [1989]; Yeaple, [1992]). Furthermore, as these data are not collected in 'real time', an investment of extra time for the respondent is also implied, and for obvious reasons this is frequently unacceptable within industry. Apart from this, they can enable an overview in a relatively short period of time, and this can even be objective owing to the time distance from the event (Blessing, [1989]). Interviews are particularly useful in this respect, especially if employed prior to other case-study techniques, as they enable at the very least the terminology used by a particular organisation to be determined (Pugh and Morley, [1989]).

- *'Real time'* - the use of 'real time' techniques is often the only means of analysing the behaviour of teams, cultures, or organisations (Blessing, [1989]). Direct observation is a non-obtrusive method that involves the observer noting features of interest whilst watching the engineering designers performing their activities. This type of data recording, however, can only capture the naturally verbalised and written performance of the engineering designers (Stauffer and Ullman, [1988]). Hence, direct observation is often substituted by participant observation, that involves the researcher both watching and participating in the process. As an insider, the researcher is able to collect more data and is in a better position to interpret these data (Blessing, [1989]). The use of this technique has been advocated by Hales [1987], who undertook a well respected observational study of a design project that lasted for 2.8 years and involved 37 people.

2.2.4 Discussion

A key objective of this research is to collect empirical data pertaining to the information flows and interactions that take place within and between the design functions of customers and suppliers engaged in product development (Section 1.6). From the previous discussions, however, it is apparent that the majority of the outlined field research techniques are either unsuited to this research or have not been previously applied in a manner akin to that required to facilitate this research.

For example, the nature of this research demands that design projects be studied from the initial need through to final manufacture. In practice, therefore, as this process may take weeks or even months, the use of techniques such as protocol analysis would clearly be impractical[8]. Moreover, in order to analyse the behaviour of the various groups in 'real-time', the use of observational methods would necessitate at least as many observers as observed, and again this is not a feasible option.

Such difficulties, however, could be overcome by the use of techniques such as involved observation, where the observed are actually involved in the analysis (Blessing, [1989]). This is a most rewarding technique in-terms of the data that are gathered, but difficult to achieve in industry; it not only demands social science skills from the engineering designers involved, but it requires considerable commitment from them in terms of both time and effort. This research has therefore demanded the use of a culmination of the empirical research techniques outlined above, together with the development and subsequent use of more appropriate 'tailor-made' methodologies. Further discussion of this is presented within subsequent chapters.

2.3 Models of Design Processes

Many of the research methods outlined in the previous section have been used in the development of models that aim to give structure to the design process. The complex and often unstructured nature of engineering design has tended to make the

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[8] In the context of engineering design research Stauffer and Ullman [1991] have reported that one hour of protocol may take up to 40 hours to analyse.

understanding of how the design process is performed in industry very difficult (Murdoch, [1993]).

However, a multitude of models of the processes that engineering designers follow and ought to be following have been developed (Andreasen, [1991]; French, [1985]; Hales, [1987]; Hubka, [1982]; Pahl and Beitz, [1984]; Pugh, [1991]; Ray, [1985]; Ullman, [1992a]; VDI 2222, [1973]; BS 7000, [1989]). The major or more established of these models are presented within the following section. Subsequent sections describe the activities associated with the phases outlined within these models, and provide an overview of the types of design activity undertaken.

2.3.1 The Established Models

A brief discussion of the models presented by Pahl and Beitz [1984], French [1985], Pugh [1991], BS 7000 [1989], and Hales [1987] is provided below. The models themselves are displayed in the figures that follow.

- *Pahl and Beitz [1984]* - this model (Figure 2.1), that has strong links with the German industrial standard for product design (VDI 2222, [1973]), is possibly the most highly developed of all of them. Akin to the model of French, it advocates a four phase design process consisting of clarification of the task, conceptual design, embodiment design, and detail design. In comparison with the other models this one places more emphasis on the conceptual and embodiment phases of the design process.

- *French [1985]* - as noted above, this model (Figure 2.2) is based on a four phase design process; consisting of analysis of the problem, conceptual design, embodiment of schemes, and detailing. This model emphasises the analysis and conceptual phases of the design process, providing mechanisms by which the engineering designers' productivity may be enhanced.

- *Pugh [1991]* - this model (Figure 2.3) shows what Pugh describes as the 'design core' of the product development process, along with a set of integrated tools and techniques to assist the engineering designer. This model emphasises the establishment and continual maintenance of the Product Design Specification (PDS), that acts as a control for all subsequent phases of the design process. In contrast to the models of Pahl and Beitz, and French, Pugh's includes the manufacture and sell phases in the model, that consists of the following broad phases: market; specification; concept design; detail design; manufacture; and sell.

- *BS 7000 [1989]* - this model (Figure 2.4) forms part of the British Standard titled "*A Guide to Managing Product Design*". It was developed as a framework to guide all levels of an organisation on aspects of product design and hence it does not consider in any great detail the tasks that need to be carried out. It is complementary to engineering management standards and serves the purpose of making organisations aware of the benefits of adhering to an engineering design process. Surprisingly, however, it indicates that design for manufacture should be performed as a distinct phase after the detail design phase, and clearly this is contrary to the philosophy of CE. This standard is currently under review (BS 7000: Part 2, [1996]).

- *Hales [1987]* - this model (Figure 2.5), although somewhat different to the others, is thought to be of particular value to the reader. Its development was based on the case study described in Section 2.2.3 together with a number of established models, such as the Pahl and Beitz model described above. It shows the engineering design process in the context of the environment and hence serves to emphasise the role that it plays in the overall evolution of a product; from demand through to disposal by the end-user. The design process activities within the model are however similar to those of the other models, and include task clarification, conceptual design, embodiment design, and detail design. This work is furthered in Hales's excellent book (Hales, [1993]).

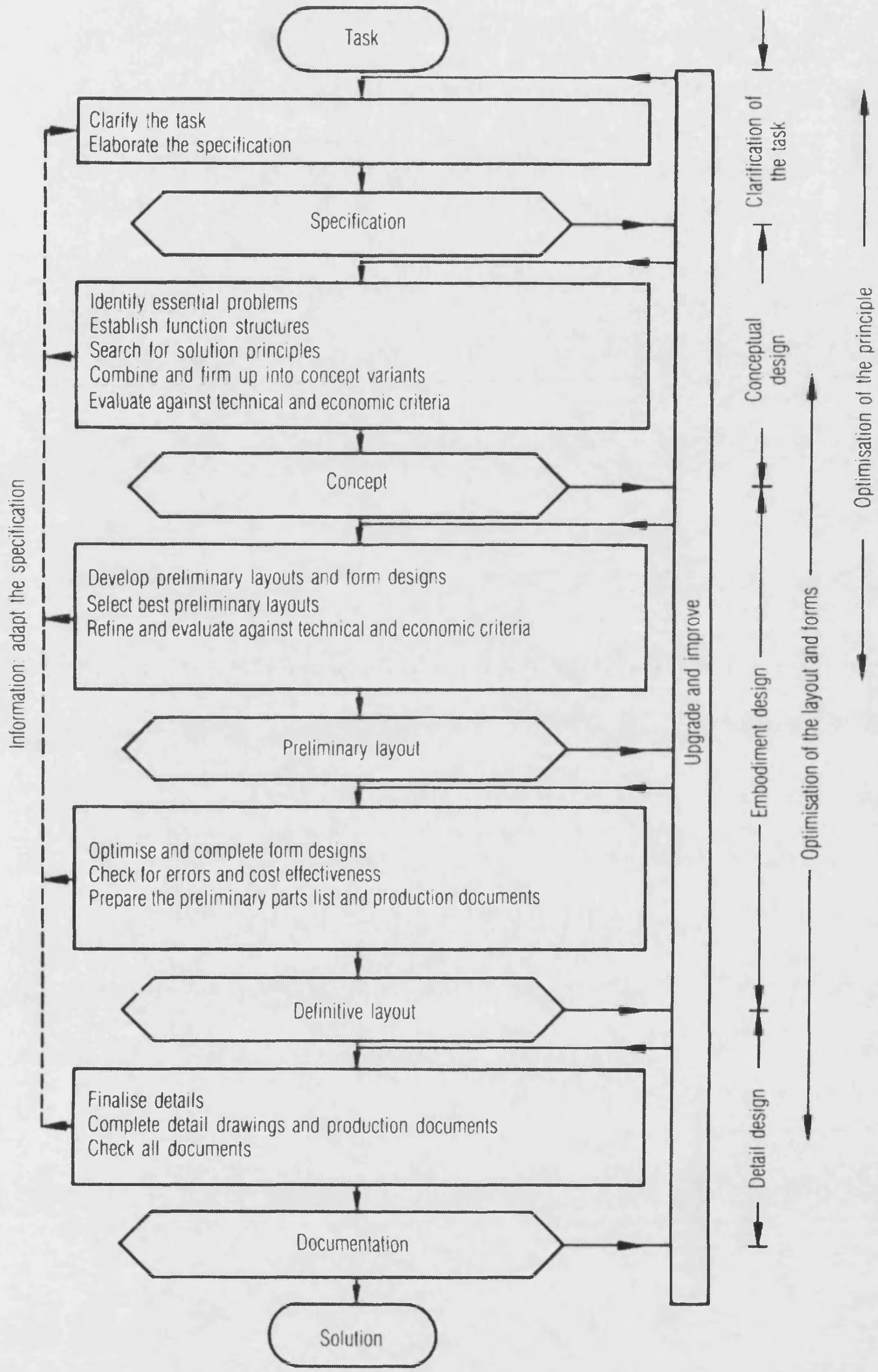

Figure 2.1: The Design Process by Pahl and Beitz [1984]

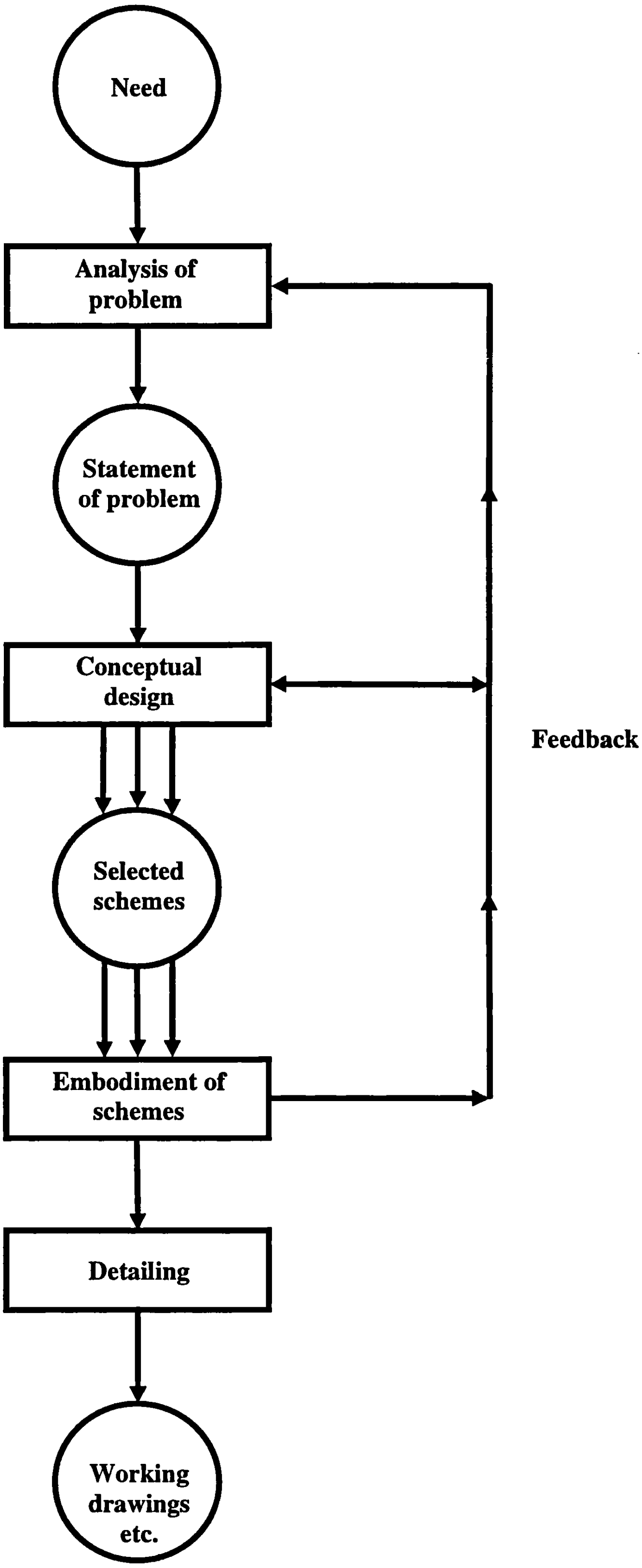

Figure 2.2: The Design Process by French [1985]

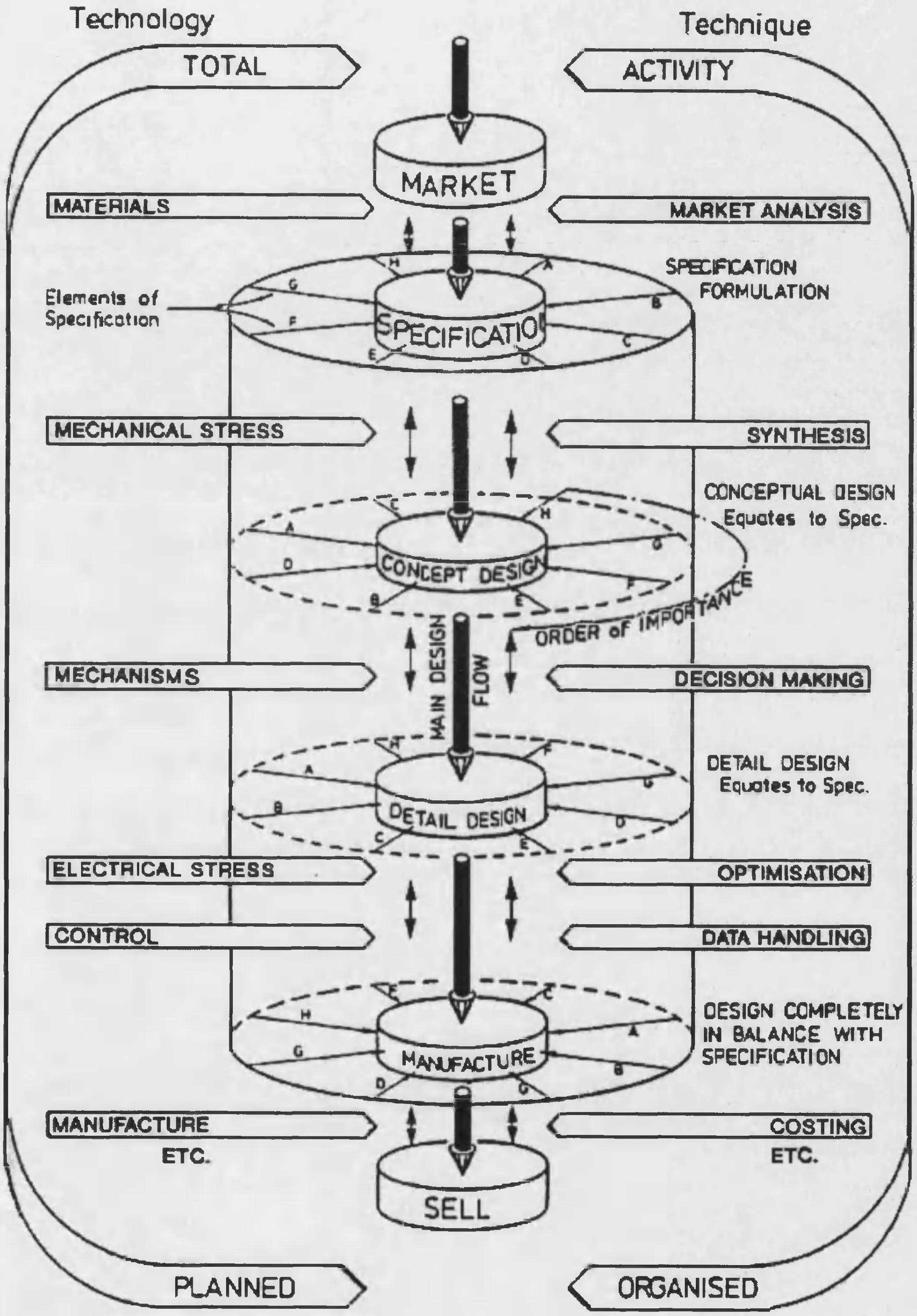

Figure 2.3: The Design Process by Pugh [1991]

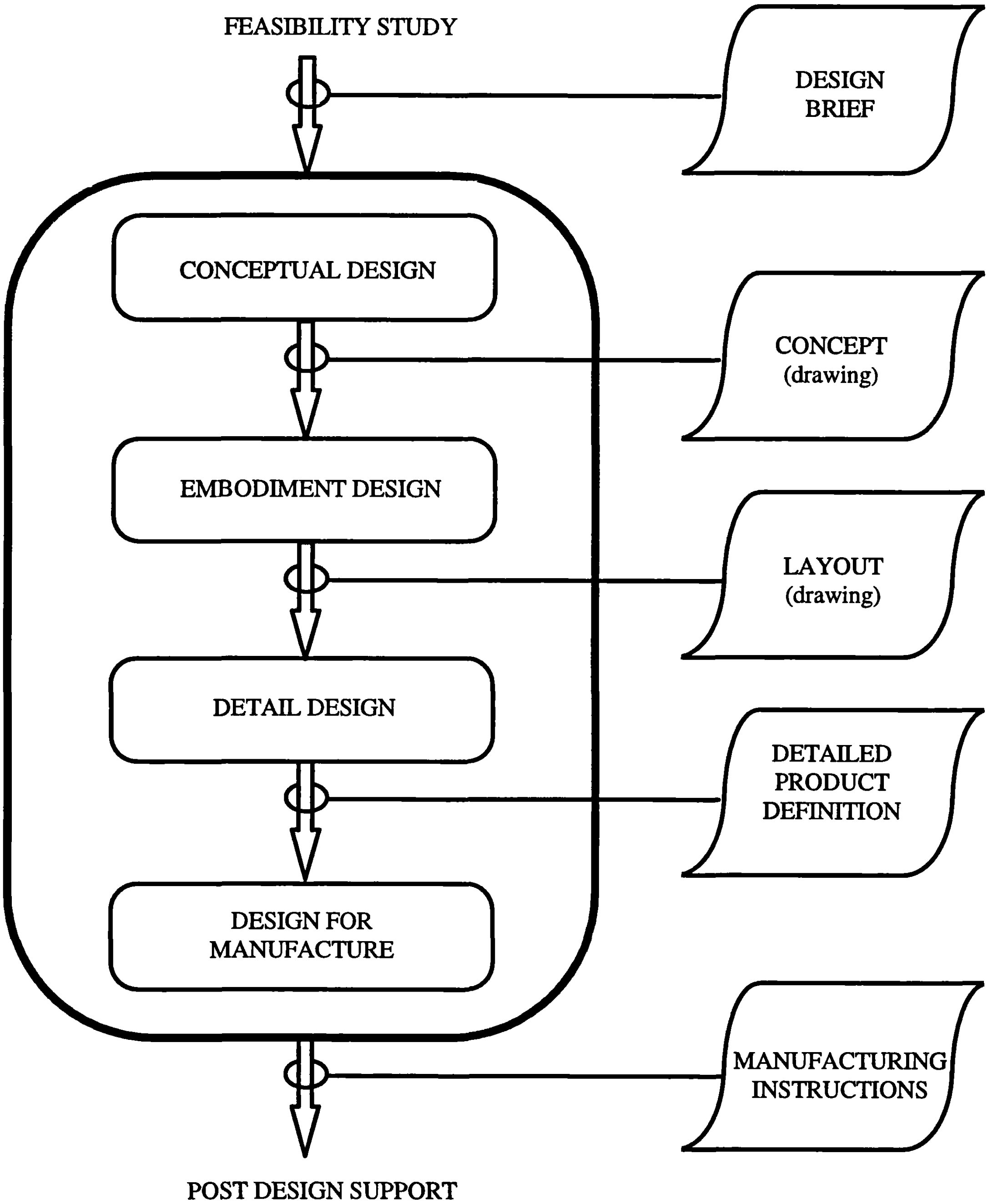

Figure 2.4: The Design Process according to BS 7000 [1989]

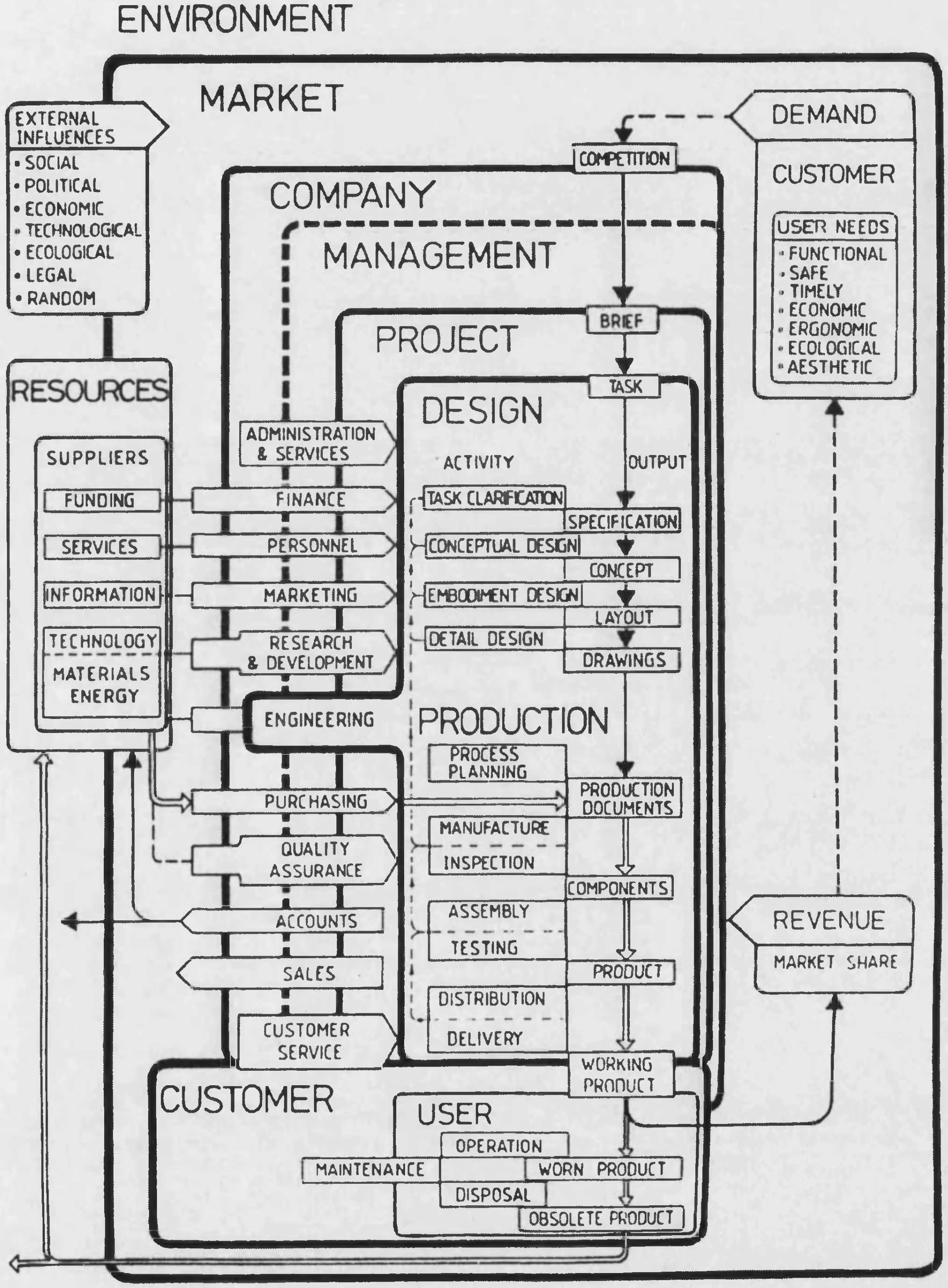

Figure 2.5: The Design Process Set in Context by Hales [1987]

2.3.2 Phases of the Engineering Design Process

The above models should serve to further emphasise that the concept of CE is not yet fully understood, as they present the design process as a serial rather than a parallel chain of activities (Schrijver and Graaf, [1996]). Moreover, with the exception of the model presented by Hales [1987], they fail to show how engineering design interacts with other functions and more importantly they make no provision for the integration of suppliers or their information into the engineering design process. Notwithstanding these points, the models do distinguish between different phases in the product development process, and an understanding of the activities and outcomes associated with these is considered to be essential.

The widely adopted phases associated with the Pahl and Beitz [1984] model, that will be used within this research, are discussed as follows:

- *Clarification of the task* - the design of a product is initiated by its requirement and this usually comes from a customer, whether internal or external to the organisation. During this phase information is collected in relation to the problem, such that it may be defined to such an extent that the customer's needs can be fully satisfied by the end product. If the customer is external to the organisation this information usually takes the form of market research and details of the constraints within which the organisation functions (e.g. manufacturing constraints). This information is then collated with the view of producing a PDS, the primary output from this phase. The PDS is usually drawn up in close collaboration with the customer. It takes the form of a document that details the demands or constraints that must be achieved by the product, along with further wishes or requirements that should be taken into consideration.

- *Conceptual design* - within this phase the needs of the customer, expressed within the PDS, are converted into a solution concept, or typically a number of solution concepts. This conversion process is often performed by decomposing the problem into a number of sub-problems that are easier to solve. In certain organisations, techniques such as Quality Function Deployment are drawn upon to aid the mapping of the needs into solution concepts (Clausing, [1994]). Much of the information that is manipulated during concept design, however, derives not from the initial PDS, but it is the implications of the PDS as manifested in potential artefacts that produce the raw material on which designers work in order to create solutions (March and Trott, [1988]). By evaluating alternatives against the known constraints and the PDS the most appropriate concept, usually in the form of a drawing sketch, can be identified. However, it is not unusual to find that more than one concept is suitable, and in these instances they may all be progressed to the next phase before the decision to rationalise is made.

- *Embodiment design* - within this phase the information and principles pertaining to the concept (or concepts) are developed into a solution that allows the engineering designer to produce a final layout of the selected design. This is a complex process that requires copious amounts of information from a wide variety of sources in order to define, for example, overall layouts and spatial compatibility, dimensions, materials, manufacturing processes, and standard components. Typically, this phase takes up a large proportion of the project effort (Hales, [1987]) and requires considerable interaction and co-ordination between team members to ensure that all areas of the design and subsequent manufacture are in-keeping with each other and the PDS. The final output from this phase will, in general, be a fully detailed scale drawing of the solution that forms the input to the detail design phase.

- *Detail design* - within this phase the embodiment layout is advanced to such a stage that it is suitable for manufacture. This is usually a fine-tuning process that involves the finalising of dimensions and tolerances, the production of detail drawings and manufacturing plans, and, finally, ensuring that the product can be manufactured in an economical manner.

With reference to the above phases, the design process models imply that they should be undertaken in chronological order by progressing the design as a whole (such that potential ideas are not overlooked) from an initial brief through to a fully detailed solution ready for final manufacture. Conversely, though, Hoover *et al* [1991] have noted that the design process is not always performed by engineering designers in a rigid manner, and a number of researchers have even advocated this as they believe that imposing a rigid structure is likely to hamper creativity and diversification (Medland, [1986]; Rothery, [1993]). Further, when attempting to decipher the underlying practices that have contributed to the success of Toyota, the most successful Japanese automotive company, Ward *et al* [1995] noted that that their development processes were not rigid.

Apart from the order that designs, or certain aspects of them, are progressed through the phases of the engineering design process, it is worth emphasising the importance of the early phases:

- It is widely accepted that by the time the early phases have been completed the overall product quality and approximately 80% of total product costs are locked in (Pelz and Andrews, [1966]; Wallace and Hales, [1989]; Schierbeek, [1989]; Rzevski and Farrar, [1994]; Bradley and Dawson, [1991]).

In turn, therefore, this should serve to emphasise the importance of integrating suppliers and, in particular, their information and knowledge into the engineering design process during the preliminary phases; a point that, as noted above, has <u>not</u> been emphasised within the aforementioned models that designers *ought* to be following.

2.3.3 Types of Design Activity

Studies of engineering design in practice have shown that a number of different types of design activity can be identified. The definitions of and the distinctions between these activities have however varied between researchers. For example, Ullman [1992a] has identified three types of design activity and classified them as original development, further development, and adaptive design, whereas Pahl and Beitz [1984] have presented three slightly different types of design activity, namely original design, adaptive design, and variant design. Vincenti [1990], however, talks of the activity of normal design, also termed conceptually static design (Pugh, [1991]). This type of design activity, that appears to encompass the variant and adaptive design activities differentiated by Pahl and Beitz, consists of the generation of a new design by incremental modifications or adjustments to an existing design.

It has been shown that the type of design activity does not significantly influence the sources of information that engineering designers rely upon during the engineering design process (Court *et al*, [1996]). However, it does influence aspects such as the level of effort and creativity that an engineering designer puts into a design. Therefore, in order to enable a balanced judgement of the subsequent methods described or proposed throughout this thesis, an understanding of these activities is considered essential.

The design activity definitions defined by Pahl and Beitz [1984], that will be used within this research, are presented as follows:

- *Original design* - this is the process of creating an original solution principle to solve the functions and sub-functions (whether the same, similar, or new) of a system or artefact.

- *Adaptive design* - this is the process of adapting an existing solution principle to solve the functions or sub-functions of a different system or artefact.

- *Variant design* - this is the process of varying existing details of a system or artefact (e.g. size or layout), such that the function and solution principle remain the same.

Reference to the research literature has indicated that the extent to which engineering designers carry out the above types of design activity has been the subject of much research attention (Pahl and Beitz [1984]; Black and Shaw [1991]; Court [1995]). In general this has established that the majority of engineering design is non-original or, in other words, redesign. Hence, there is a clear need to structure and store past design data, information, and knowledge, such that it can be effectively reused time-and-time again. The tools currently available to support engineering designers in these activities will be discussed in due course.

2.4 Concurrent Engineering

Engineering design and manufacture have traditionally been managed in a serial or sequential fashion; requirements definition, design, analysis, production engineering, and manufacture were accomplished end-to-end and with limited interaction. Engineering designers completed their work and passed the detail drawings to production engineers, whose job initially was to decide how to manufacture the artefact. The lack of feedback and communication between these two major departments, however, often resulted in designs that were sub-optimal or even unsuitable for manufacture (Carter and Baker, [1992]). Iterations that resulted in design modifications were therefore commonplace. Further, after an artefact had finally been manufactured it was passed on to the assembler only to find that assembly was difficult, costly, or sometimes unfeasible. Hence, the sequential or appropriately termed 'over-the-wall' process was essentially flawed.

Owing to the trend in the early 1980's of increasing product complexity, rapid developments in innovative technologies, and pressure to reduce product development times, the desire for a new product development method was born. This method, that was partly founded on the results of a 5 year study by the Defence Advanced Research Projects Agency into improving concurrency in the design process, did not really emerge however until the mid to late 1980's (Carter and Baker, [1992]). It has subsequently been termed simultaneous or Concurrent Engineering (CE). Comprehensive views and case examples of CE can be found in Whitney *et al* [1988], Carter and Baker [1992], and Clausing [1994].

A CE environment is one in which *all* the disciplines required to develop and bring a product to market, complete with its support services, move through the phases of the design process in a concurrent manner (McLeod, [1991]). Each phase results in decisions, documents, revised schedules, and objectives that all disciplines have contributed to create more actively than is likely using the sequential approach (Almli, [1988]). A pictorial representation of these two different approaches is shown in Figure 2.6.

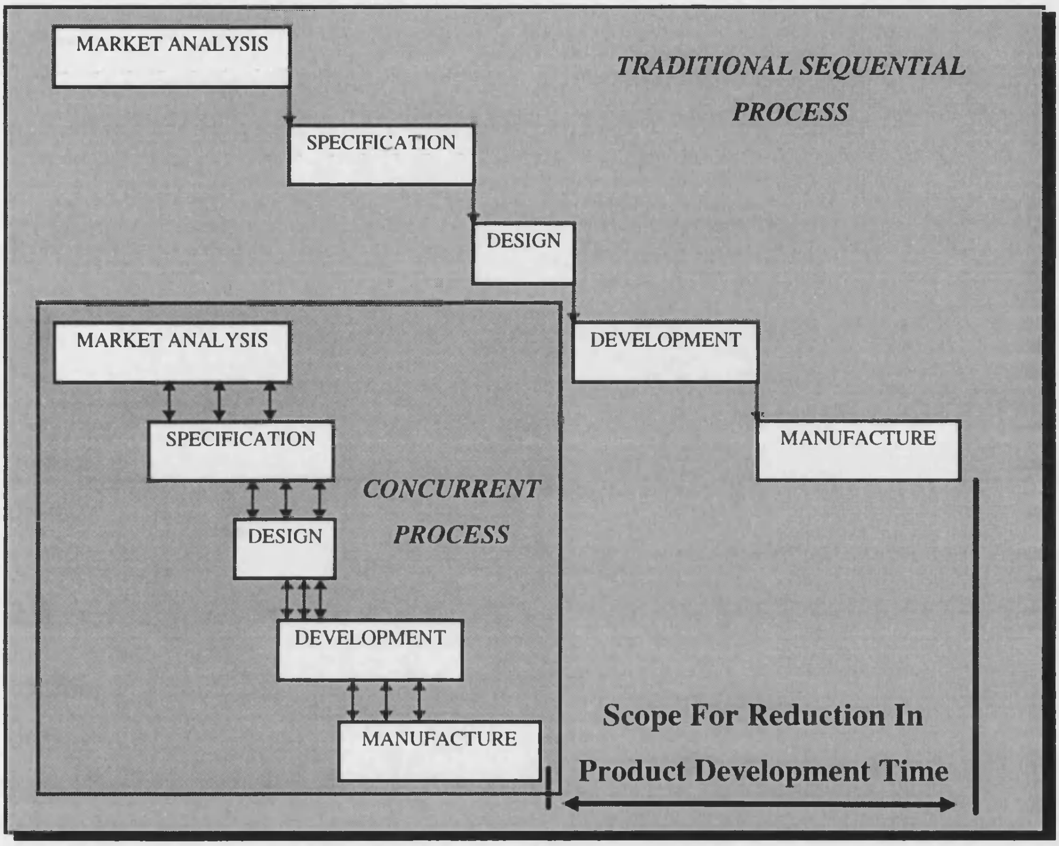

Figure 2.6: Traditional Versus Concurrent Engineering

Organisations that have successfully managed to implement CE can be credited with profit increases (as a percentage of sales) of up to an estimated 26%, together with improvements in the following main areas (Carter and Baker, [1992]):

- Products that are more producible.
- Products that are of better quality.
- Products that better adhere to needs.
- Reductions in overall cycle times.

With cited benefits such as these it is hardly surprising that CE has been the subject of much research attention. Finger and Dixon [1989] have classified this research into two not totally independent perspectives, namely:

1. *Process* related studies.
   - This focuses on organising and controlling the design process to enable early concurrent consideration of life-cycle issues.

2. *Knowledge* related studies.
   - This focuses on acquiring, organising, and utilising knowledge of life-cycle issues that relate to early design decisions.

The following sections present key aspects from the above two perspectives and discuss issues pertaining to the integration of suppliers into the CE design process.

2.4.1 Design Process Requirements for CE

In order to realise the full potential of CE the various disciplines need to be involved during the early phases of the engineering design process (Pye, [1990]); a consequence of the fact that within these phases overall product quality and the vast majority of total product costs are built in (Section 2.3.2). Owing to the nature of these phases, however, these disciplines not only need to be involved but they also need to be able to actively collaborate.

Within the early phases of the design process information is constantly accessed, reinterpreted, and reapplied as product concepts are conceived, explored, and rejected (Majumder and Fulton, [1990]). Moreover, much of this information tends to be of an informal and opinionated nature and it is not until the design process proceeds (from C towards A in the 'Boston' {N.B. this does not refer to the author} matrix shown in Figure 2.7) that it becomes more static, formal, and factual (Wright and Swain, [1995]).

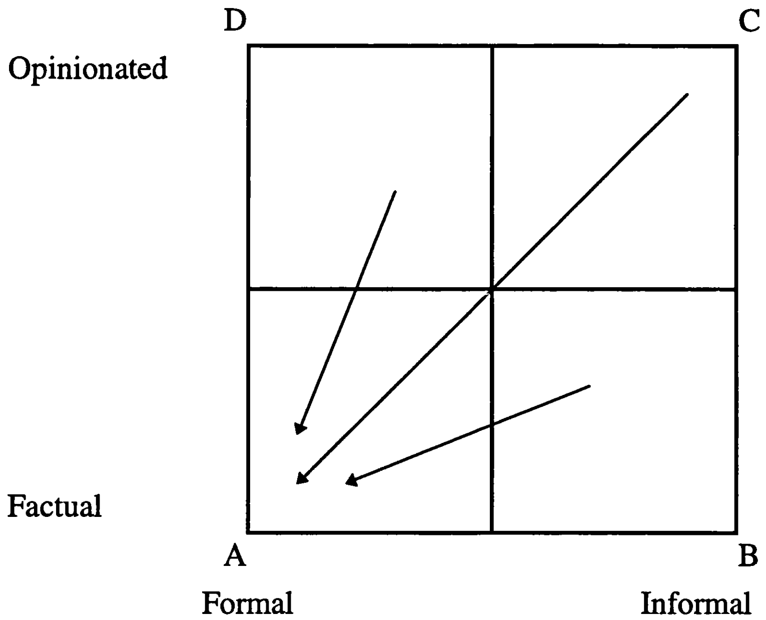

Figure 2.7: Types of Information and the Trend Towards Type A (Wright and Swain, [1995])

The early phases of the design process are therefore the subject of many communications and much ambiguity and uncertainty. As a consequence, the use of face-to-face communication has been advocated within them[9] (Yeaple, [1992]; Davis, [1991]; Gralewska-Vickery and Roscoe, [1975]; Shotwell, [1971]). This is owing to the fact that high rich[10] communication media are better suited to this type of information than low rich communication media (Figure 2.8); facial expression or tone of voice can convey information far beyond that of the spoken word (Holland *et al*, [1976]).

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[9] Both Rangan and Fulton [1991] and Daft and Lengel [1984] have implied that face-to-face communication may not always be suitable. For example, when communicating simple phenomena this medium may be inefficient and, of further significance, facial expression or tone of voice may distract from the spoken word.

[10] The term 'richness' is widely used in the information theory related literature. It has been defined by Daft and Lengel [1984] as "*...the potential information-carrying capacity of data*".

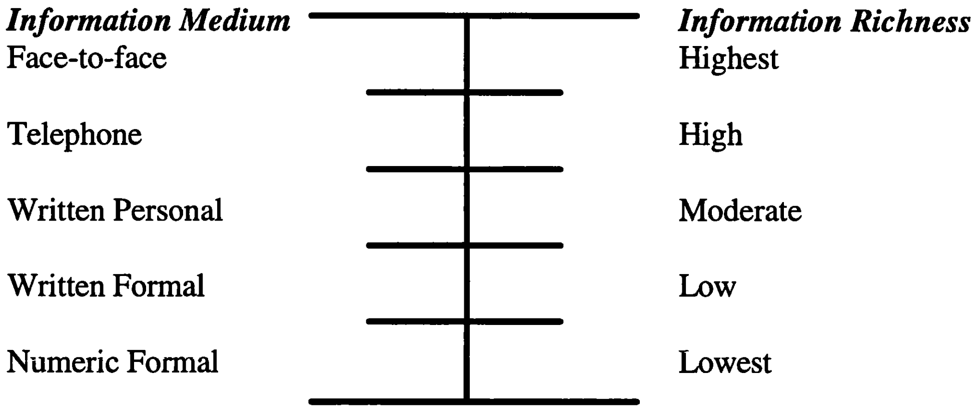

Figure 2.8: Information Media and Richness

(Adapted from Daft and Lengel [1984])

In turn, the above requirement has called for the utilisation of multidisciplinary teams, that include members specialising in, for example, design, production, assembly, procurement, etc..

2.4.2 Knowledge Requirements for CE

Simply bringing together experts is only one part or aspect of CE, it requires the transfer of the right quantity of information to the right individuals at the right time (Christian and Seering, [1995]; Lindeman and Wijaya, [1992]). With the traditional or sequential design process this was not a problem, as information was accumulated during each phase until it was practically complete before transferring it to the next phase. In CE environments, however, the activities are performed in parallel and hence information has to be transferred and co-ordinated between team members. Further, this information may have come from an incomplete or a current phase and hence team members frequently have to work with partial information and subjective interpretations (Almli, [1988]). The CE design process is therefore likely to create more short term 'mistakes' than the sequential one, but ultimately it leads to fewer iterations and significant reductions in overall product development times (Nukala *et al*, [1995]). The extent to which these can be reduced, however, is dependant upon the amount of overlap and interaction that can be achieved between phases and, in turn, this is dependant on how early and quickly the first stage can provide enough information for the second to commence (Clark and Fujimoto [1988]; Smith and Reinersten, [1991]).

As may be evident from the above, successful CE demands efficient communication networks and adapted procedures (Schierbeek, [1989]). The importance of this has been emphasised in the "Guide to managing product design" (BS 7000, [1989]) where, despite showing a sequential process, it is stated that *"The complex activity of product design can not be performed effectively if communication is haphazard or unstructured*". Conversely, however, Rangan and Fulton [1991] have noted that within many engineering organisations *"there is a large amount of 'adhockery' in the information transfer mechanisms*"; a remnant, perhaps, of the traditional sequential product development process existing within a multi-layer hierarchy (Carter and Baker, [1992]).

It is thus clear that CE requires changes in the patterns of information flow and the methods of communication (Fleischer and Liker, [1992]). Conversely, though, Sonnenwald [1996] has noted that "*...not much is known about communication during the design process...*", and Fox [1994] has noted that previous research has not fully addressed issues pertaining to the co-ordination of decisions and the interactions and interfaces between team members. As a consequence, therefore, there are a lack of general guidelines or theories on how to implement and manage these changes for CE (Fox, [1994]). The need to overcome these deficiencies has thus called for studies of the engineering design process from an information exchange standpoint. The outcome of this, as noted by Sonnenwald [1996], may also "*...provide an insight into new design methods that explicitly include communication strategies*" and "*...possibly new computer-based tools that support communication roles during the design process...*".

2.4.3 The Integration of the Supplier

Influential factors in the realisation of CE are, as previously implied, the location of and the relationships between the functional specialists who need to bring to bear expertise upon an emerging design (Cunningham and Homse, [1984]; Bush and

Frohman, [1991]; Smith and Reinertsen, [1991]). In an attempt to meet these needs when suppliers are involved in the design and development of new products, a number of significant changes have taken place. Most notably, however, these changes have taken place within large or multinational organisations and, in particular, they have tended to focus at fairly high levels of abstraction. As a consequence, therefore, information issues at the level of the engineering designer have received insufficient attention (Harland, [1995]). This, as outlined below, is considered to be especially so within small to medium sized organisations.

Changes in the relationships between customers and suppliers in order to overcome clashing contractual and commercial styles and to establish common practices is now seen as essential (Sanford, [1989]). In order to facilitate this organisations have, for example, reduced their supply bases such that they can focus management time and attention, and in turn this has enabled the concept of a partnership as opposed to the often adversarial transactional customer-supplier relationship to be developed (Hogg, [1993]). In such scenarios, practices such as open-book accounting; cost transparency; agreements on supplier assessment schemes; and benchmarking are not uncommon (Lamming, [1993] and [1994]).

In certain industries, such as the Japanese automotive industry, these relationships have been developed to such an extent that suppliers are seen to be an extension of the customer's own organisation, with the same values, the same commitments, and the same productivity goals (Hogg, [1993]). Indeed, Womack *et al* [1990] have even cited examples of major component and sub-system suppliers locating or being forced to locate in close proximity to a customer's major factories. The desire of the customer to be as successful as possible, however, means that they need their suppliers to be successful and consequently they help them in any way possible. One way by which they do this is to provide them with 'resident engineers'; a team of engineers from the parent company, who spend a period of time assisting the supplier in the early stages of product development.

When considering smaller engineering organisations, however, it is clear that it would not always be economically viable or even feasible for them to collocate their suppliers. Similarly, the use of 'resident engineers' may also prove both costly and place a significant strain on the resources of smaller organisations. It is thus apparent that in the majority of multi-organisational product development situations[11] geographic distance may form a barrier[12] to the practice of CE. In turn, therefore, organisations will have to rely upon alternative types of communication media, and a number of these do in fact have benefits in other areas over and above those for face-to-face communication. For example, Electronic Data Interchange (EDI) has been cited as providing benefits in the following areas: paper elimination; increased internal efficiency; more efficient business practices; faster flow of data and hence the flow of goods and money; long term partnerships; and the accessing of new markets (Blotwijk, [1993]; Henderson, [1989]). In the light of these benefits, it is hardly surprising to find that many organisations are imposing EDI on their suppliers (often for the purpose of exchanging drawing data[13]) who in-turn are doing the same with theirs (Rothery, [1993]).

However, these emerging communication solutions are still not ideally suited to the rapid transfer, across organisational boundaries, of the <u>information</u> necessary in the preliminary phases of product development (Sanvido *et al*, [1989]). Moreover, Hameri and Nihtilä [1995], during a study of several hundred participants using electronic communication in new product development, noted that that periodic face-to-face communication is a necessary prerequisite for all kinds of collaboration, be it electronic or not. Furthermore, these emerging communication solutions will not deliver their potential, and may even worsen the situation, unless the current situation is fully understood and subsequently the nature of work within organisations is re-

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[11] Liker and Hancock [1986] noted that even within the confines of an (automotive) organisation attempted face-to-face contacts were successful only 32 % of the time.

[12] In a survey of engineering designers, Yeaple [1992] reported that the majority only had direct contact with their suppliers once or twice a year and some had none at all.

[13] During a survey undertaken by Wardle [1996] it was revealed that 46% of organisations had reported problems exchanging drawings with suppliers and customers using conventional means.

structured to take account of recent demands (Konsynski and Warbelow, [1989]; Harrison and Minneman, [1993]).

2.5 IT Support and Product Representation in Design

It should be apparent from the previous sections that information is a key element of product diversification, concurrent engineering, and continuous improvement (Court *et al*, [1997a]). Unsurprisingly, therefore, IT-based tools to support its storage, management, manipulation, and representation have not only been attributed to the majority of the estimated 50% growth in output from the design office since the turn of the century (Helmreich, [1985]), but they have also been cited as a major advance and driving force in design today (Whitney, [1990]). The following sections will provide an overview of these developments with the view to highlighting those areas of design that are both supported and currently unsupported by IT.

2.5.1 Information Storage and Management Tools

The amount of information available to engineering designers is increasing at a staggering rate (Ehrlenspiel, [1997]). Today, for example, suppliers may produce standard component catalogues detailing over 500 widgets, whereas 10 years ago these catalogues may only have listed around 50 (Brooks, [1998]). Engineering designers are thus, to quote from Fox [1994], "*...drowning...*" in information. Yet, from this large and expanding pool of information, they are increasingly expected to find that which is accurate, relevant, and current, and to do so in a timely or efficient manner (Boston *et al*, [1997b]). Further, Court *et al* [1997a] have noted that if they cannot access this information in an efficient manner they may not access it at all. Hence, the need to support and pay close attention to its organisation and handling is evident.

In an attempt to aid engineering designers in the above activities a number of IT-based tools have been developed. In general, it is considered that these tools may be grouped into two categories, as discussed below:

1. Those that are intended to 'manage' a defined set of commercially available information.
   - For example, Vogwell and Culley [1991] developed the *Electronic Catalogue*; a system that would enable an engineering designer to rapidly select[14] a suitable bearing for an application from a database containing over 22 000 bearings of 34 different types from 10 major manufacturers. Commercially available derivatives of this system now enable the selection of a wider range of components, such as springs, gearboxes, seals, and belt-drives. Increasingly, manufacturers are providing access to these systems over the World Wide Web (IED, [1998]). Owing to factors such as poor search facilities, however, their usefulness in this manifestation appears to be the subject of much debate (Borgman, [1996]).

2. Those that are intended to 'manage' a set of information defined by the user or users of the system.
   - These include, for example, document image management and data-base systems that are capable of storing soft electronic data and scanned images of hard data. Compared to manual systems, Botterill [1992] estimated that they may reduce the time taken to access and return a document from two days to two hours, and in a similar vein Sanford [1989] has estimated that if effective they have the potential to generate savings of between 2 and 5% of total project costs.

According to a number of researchers, however, the above systems, and in particular the bespoke systems, are not without their problems, for example:

- Bögler [1995] reported that six out of ten big British organisations have suffered a major failure with their computer systems in the past two years, and 35% of those were related to a breach of security.

[14] A time consuming and laborious activity which has been estimated by Cave and Noble [1986] to take up to between 20% and 30% of an engineering designers time.

- Poon [1991] stated that improperly designed systems may impede information flow and they can lead to the duplication of information and the compounding of human errors.

- Salzberg and Watkins [1990] and Levy *et al* [1993] noted that such systems will only be utilised by engineering designers if the amount and quality of information within them is above some threshold.

- Court *et al* [1997a] noted that implementing and even updating such systems is a distinct problem, and this in itself may serve to explain that the fact that only 6% of the 200 organisations surveyed by them used such systems.
  - One further and significant issue highlighted by Court *et al* [1997a] is that on the whole engineering designers "*...still prefer to use manual and verbal methods of communication and information retrieval*".

It should be apparent from the above that current IT-based information 'management' systems do not fully meet the needs of engineering designers. Hence, there is a clear need to overcome this deficiency and, of further significance, to play close attention to traditional or manual systems in the mean time.

2.5.2 Information Manipulation and Representation Tools

IT-based tools are available to support engineering designers in a broad and increasing range of activities; a selection of these were highlighted in Section 1.3. Their ability to enable more to be achieved with fewer people and in less time has, in recent years, been aided considerably by developments in Knowledge-Based Engineering (Anderson, [1994]). This is a computer system that enables the creation of a fully engineered best practice design by storing the experience, geometry, and data that relates to a product (Kneebone and Blount, [1997]). Key aspects of research in this area include the re-use of product knowledge by integrating Knowledge-Based Engineering models with standard product models. These are used to represent a complete product throughout its life-cycle and, in general, are made up two core elements, namely geometric and functional models. The following sections therefore provide an overview of geometric, functional, and product modelling; key areas in which the engineering designer is supported by IT.

2.5.2.1 Geometric Modelling Tools

Geometric modelling, commonly referred to as CAD, is the general term given to the activity that utilises a computer-based system for the representation of an artefact in terms of its dimensions. The CAD systems of today are highly sophisticated and considerably more powerful than the early ones, that were little more than electronic pencils (Esterline *et al*, [1988]; Whitney, [1990]). The advent of 3D solid modelling systems, for example, has greatly enhanced product visualisation; a solid model is the closest[15] representation that a computer can make to a designed artefact (Medland, [1986]). It is hardly surprising therefore that the utilisation of CAD systems is becoming an integral part of the design process for many organisations. In fact Carter and Baker [1992] have estimated that around 80% of all designs will be created on CAD systems in 1999.

However, the use of CAD systems is very much restricted to the later stages of the product development process when the geometry of an artefact is reasonably well defined. Hence, such systems cannot support the engineering designer in the early stages of the design process where the cost and quality of an artefact are largely determined (Lawrence, [1990]; Cartmell *et al*, [1993]; Baya and Leiffer, [1995]). Further, Toye *et al* [1994] have noted that "*CAD systems do not support the tasks on which engineers spend the most time: gathering and organising information, communicating with clients, suppliers and colleagues, negotiating trade-offs and using each others' services*".

2.5.2.2 Functional Modelling Tools

Function has been defined as the conversion between the inputs and the outputs of the system and its sub-systems (Pahl and Beitz, [1984]). Functional modelling tools

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[15] Advances beyond this are possible with rapid prototyping, but this also demands use of CAD.

are used to represent the functional rather than the geometrical intent of an artefact. They are however at an early stage of development and, in general, specific to well-defined classes of design problems. A taxonomy for this has been proposed by Finger and Dixon [1989], namely parametric design, configuration design, and conceptual design:

- *Parametric design* - this is the process of assigning values to known attributes of an artefact, where these values may be numeric or type designation, for example, a material choice or a bearing type. Computer-based parametric design tools are the most mature of the functional modelling tools. An example of such a tool for designing simple assemblies and systems is described by Ward and Seering [1990].

- *Configuration design* - this is the process of converting the functional representation of a concept into an embodied design with a defined set of attributes, but with no particular values assigned to them. Computer-based tools to support this activity can be grouped into two main areas, namely development of an assembly from a set of standard components, and development of non-standard form by redesign or directly from functional requirements (Finger and Dixon, [1989]).

- *Conceptual design* - this, as already described, is the process of converting functional requirements into a physical embodiment or configuration. Computer-based tools to support this activity effectively synthesise functional solutions from a functional description of the problem. Examples of such tools are provided by Ulrich and Seering [1989].

2.5.2.3 Product Modelling

The purposes of product modelling[16] include the representation of product data[17] throughout the life-cycle of a product. This involves the modelling of multiple aspects of the product[18] such that these can then be seen from different viewpoints of parties involved (Leeuwen *et al*, [1995]). For the purposes of enhanced communication, product data needs either to be exchanged between parties or integrated in shared models. In turn this has brought about the need for standardisation of data definitions and exchange; needs that were recognised by researchers in the early 1980's (Shaw *et al*, [1989]).

Initial attempts to meet the above needs resulted in the development of standards such as IGES, that were primarily concerned with the exchange of information intended for human interpretation. More recently, however, attempts to meet these needs are being made with formal data definition languages such as EXPRESS and formal data and product model exchange standards such as STEP. These are primarily concerned with information intended for interpretation and use by computer systems such as CAD/CAM, and hence they are of major interest to the design community (Finger and Dixon, [1989]).

In contrast, however, Leeuwen *et al* [1995] have noted that current product modelling approaches are rigid and static in nature and thus they not ideally suited to support the early stages of the engineering design process. Further, they also noted that if they are applied to these phases the creativity of engineering designers is likely to be hampered.

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[16] To clarify, information modelling (to be discussed in Chapter 4) is <u>not</u> the same as product modelling. As Wilson [1987] states; "*It is not particularly concerned with how the information is represented in terms of data; neither is it concerned with how the information could be manipulated by a computer system. It is concerned with capturing and defining the "human" view of "meaning". For convenience it is useful if information models are available in computer-sensible form, but this is not necessary.*"

[17] See Section 4.2.2 for a distinction between data and information.

[18] Aspects of design, costs, assembly, manufacturing, planning, etc..

2.6 Summary

This chapter has provided an overview of some of the important aspects of research in engineering design, and the techniques that are frequently employed to carry it out within the domain; particular emphasis was placed upon both suppliers and information. Within this, an insight was given into the way that engineering design is practised, and the tools and techniques that are currently available to support it.

More significantly, this chapter has emphasised the vital role that information plays within the design and development of new products. Its communication, co-ordination, and management were seen to be key aspects in the realisation of CE and the successful integration of suppliers. Conversely, however, it was shown that these information related activities were poorly understood and, as a consequence, not well supported. For example, it was revealed that little is known about communication in the design process or how the patterns of information flow should be structured to achieve success. It was noted that the prescriptive design process models placed limited emphasis on information and provided no indication as to how suppliers and their information may be integrated into the design process, especially in CE environments. Further, it was also shown that current IT-based tools do not fully support engineering designers in the early stages of the engineering design process, or even in the activities on which they spend a large proportion of their time, such as gathering, organising, and communicating information. Moreover, it was suggested that engineering designers may even prefer manual rather than computer assisted methods of information retrieval and communication.

Subsequent chapters of this thesis present the research work undertaken by the author in an attempt to address some of these issues. The following chapter focuses on standard supplier literature and how it is organised and handled within design functions; the first of the two parallel lines of investigation (Section 1.7).

Chapter 3. Standard Supplier Literature

This chapter focuses primarily on standard supplier literature; the first of the author's two parallel lines of investigation. It reviews the research literature in order to establish both the role that it plays in the engineering design process and the factors that impinge upon its utilisation. Subsequently, it presents and discusses the results of an in depth investigation into the organisation and handling of this information source within a small to medium sized engineering organisation. This covered issues such as classification, age identification, currentness, and what in general may be termed the life-cycle management of supplier literature.

A number of the pertinent findings presented within this chapter were subsequently reinvestigated over a larger sample size by way of a questionnaire survey; detailed in Chapter 7.

3.1 Introduction

With the expansion of today's global engineering markets, competitive advantage accrues to those organisations that can produce products that incorporate diverse technologies, are of enhanced quality, and are brought to the marketplace sooner (Smith and Reinertsen, [1991]; Lamming, [1993]).

The ability of organisations to achieve these objectives, however, is dependant upon the efficient and effective management of design information (Court *et al*, [1997a]), for example:

1. If information used is not current or accurate then:
   - ➢ Innovation may be constrained or mistakes or misjudgements may be made on aspects of the products' design (CIS, [1996]).
     - This could result in products that are sub-optimal, products that are built around discontinued technologies, or even the catastrophic failure of products (Court *et al*, [1997a]).

2. If information is poorly structured then:
   - ➢ It may be overlooked or engineering designers may be unable to locate it in the available time (Macleod *et al*, [1994]).
     - In either instance design decisions may be based on incomplete data and assumptions and they are therefore likely to be sub-optimal (Rangan and Fulton, [1991]).

3. If information is not readily accessible then:
   - ➢ Product development times may be increased; by up to an estimated 48% (Yeaple, [1992]).
     - In the case of a car that sells for $10 000, each day of delay in market introduction may cost an organisation over $1 million in lost profits (Clark, [1989]).

It is thus clear that there is a need to pay close attention to the management of information within the design and development of new products[19]; a need that that is especially evident in the context of information that relates to the preliminary phases of the design process, as these have been shown to be the most sensitive in terms of overall product cost and quality (Section 2.3.2).

Engineering designers, however, utilise information from a vast array of different sources; that may be internal or external to an organisation; that may be presented in

[19] It is worth emphasising that if a design project fails the losses may be much higher in CE environments than in traditional environments as the initial 'up-front' expenses are usually much higher (Ebert *et al*, [1986]).

a multitude of formats (Court *et al*, [1993]). It is self evident that an investigation of the management methods for each and every information source is beyond the scope of this research. Therefore, the following sections identify one of the information sources that is commonly used within the preliminary phases of the engineering design process; outline what is known about how it can be managed; investigate how it currently is managed within industry; and draw some general conclusions and recommendations as a direct result of this research.

3.2 Information Utilisation in the Preliminary Phases

As long ago as 1969 it was revealed that that supplier information was widely used in the preliminary phases of the engineering design process (Allen, [1969]; Wolek, [1969]). Ten years later Bottle and O'Connor [1979] reported similar findings during a survey of the information seeking patterns of engineering designers. Almost a quarter of century later these findings were reiterated by Bond and Ricci [1992] during their studies of engineering designers in the aircraft industry.

Further reference to the research literature, however, has indicated that engineering designers may access this information indirectly from suppliers, and in fact via the information that they already possess (Wolek, [1969]). More specifically, Court *et al* [1996] have shown that engineering designers frequently access supplier information from personal and organisational stores of standard supplier literature. This literature, that typically includes catalogues, handbooks, and datasheets, is produced by the majority of manufacturing firms in order to represent their capabilities or, more usually, a range of standard components made by them (Turner, [1977]).

The benefits that may accrue from utilising standard components have been summarised by Leech and Turner [1985] as follows:

- *Improved quality* - since they are designed, manufactured, and proven by specialist manufacturers.

- *Reduced costs* - since they are manufactured in large volumes and available off-the-shelf.

- *Reduced time to market* - since they require no time to design and very little to manufacture.

In view of these benefits it is hardly surprising that standard components are frequently incorporated within the design of new products; a practice that often demands reference to standard supplier literature, and one that has been advocated by many practitioners and researchers alike (Pahl and Beitz, [1984]; Shigley, [1986]; Ullman, [1992a]).

It should be emphasised, however, that the demands placed upon supplier literature are not solely for the purposes of selecting standard components. For example, Court *et al* [1994] noted that supplier literature was frequently used as a source for application examples and installation techniques, for the purposes of performing life and load calculations, and for guiding specific analytical or procedural design activities; Stauffer *et al* [1987] noted that supplier literature was used when designers possessed little domain knowledge and wanted to find what was available off-the-shelf, to check the properties of some form, or simply to spark some ideas; and Turner [1977] even stated that "*Many **good** designers seem to **start** their information search from **catalogues** where well produced diagrams give clues via a high impact visual representation*" (author's emphasis).

Further, this present research has revealed that standard supplier literature is perceived by engineering designers as being one of the most valuable sources of information about new products, materials, and technology advancements in general; second only in fact to direct contact with suppliers (Section 7.6.4). This, together with the discussions presented above, should serve to explain the fact that standard supplier literature is one of the most frequently used sources of information in the early phases of the engineering design process (Radcliffe and Lee, [1991]); a point that is exemplified by Schwarzwalder [1992] who has described it as being an indispensable tool for the working engineer.

3.2.1 Discussion

In summary, the quality and cost of an artefact are largely fixed within the preliminary phases of the engineering design process, and control over these factors is dependant on the information utilised within them. A key source of this information is standard supplier literature, that is used not only for the purposes of selecting standard components but for sparking ideas, performing life and load calculations, establishing application and installation techniques, etc.. Hence, there is a clear need for the totality of this information to be accurate, current, and accessible, especially considering the current pressures that engineering designers are working under, where time constraints may not allow the amendment or even verification of poor quality information.

To-date, however, there are a lack of procedures, guidelines, standards, or books that specifically indicate how standard supplier literature should be managed within industry; a consequence, perhaps, of the fact that such aids do not even exist for engineering information in general (Court *et al*, [1996]). Moreover, it is also apparent that research into how this information source is currently organised and handled within industry and whether or not current systems and procedures are appropriate also appears to be lacking. Yet, in view of the rapidly increasing volumes of standard supplier literature (Brooks, [1998]) and the fact that engineering designers already spend around 25% of their time searching for and accessing information (Section 1.4), the need to address these issues is evident.

The following section will therefore provide an overview of factors that impinge upon the utilisation of standard supplier literature. Subsequent sections present and discuss the results an extensive investigation into the organisation and handling of supplier literature within industry.

3.3 Effective Utilisation of Supplier Literature

With reference to Section 3.1, it is apparent that effective utilisation of standard supplier literature is dependant upon the way that it is organised. In fact, Devine and Kozlowski [1995] state that:

> "*Processing limitations inherent in cognition imply that the efficient organisation of information is crucial to effective task performance in most situations*".

For large volumes of information, however, Salustri and Venter [1992] have noted that an efficient classification system is needed to facilitate information retrieval; in its absence the designer is faced with, what Court *et al* [1996] have termed, an "*information overload*" situation. Hence, the following section will provide an overview of classification and how it has been applied within the domain of engineering design.

3.3.1 Background to Classification

Classification is defined in the Oxford Dictionary [1991] as *"...arrange in classes or categories; assign (a thing) to a class or category..."*, and within the Librarians' Glossary and Reference Book (Harrod, [1984]) as *"...the arrangement of things in a logical order according to their degrees of likeness..."*. Many different classification schema have been developed, such as those used for the classification of plants in botany, animals in biology, rank in the forces, or books in a library.

As noted by Langridge [1992], classification schema cannot be judged as being either right or wrong, only as being more or less good for their purpose (or purposes in some cases). When developing classification schema, however, there are a number of basic principles or guidelines that should be adhered to, for example:

- *Mutual exclusivity* - a classification should be mutually exclusive; it should include similar things while excluding dissimilar things, using clearly defined parameters.

- *Static verifiable characteristics* - a classification should be based on attributes or characteristics that are permanent, unchanging, and clearly visible (or easily verifiable).

These principles were established early on in the development of traditional schema. More recently, however, primarily as a result of the Brisch Classification (Gombinski [1969]; Hyde [1981]), two more principles or guidelines have evolved:

- *All embracing* - a classification should cover all existing items and be capable of expansion in order to accept additional or new items into the defined population.

- *User's viewpoint* - a classification should be developed from the perspective of the user and not from the perspective of the person developing the classification.

Inherently linked to classification are the principles of coding; coding is the process of assigning one or more symbols to a thing with an arbitrary meaning and/or arrangement, and when a code is deciphered specific information is communicated (Jack, [1989]). The use of coding is particularly important in large classifications; in its absence classifications would become, as Jack [1989] states, *"...cumbersome and inefficient"*.

Akin to classification, there exist a number of basic principles or guidelines for coding, such as those presented by Jack:

- *Code length* - this should not be in excess of 5 characters without a break in the code string.

- *Code pattern* - the code string should be consistent, both in terms of its pattern and its length.

- *Numeric codes* - all-numeric code strings are considered to produce the least number of errors.

- *Alphanumeric codes* - these are acceptable if the alpha field is fixed and is used to break up a string of numbers.

The following are some of the better known classifications, some of which utilise coding: Decimal Classification (Dewey, [1965]), Linnaeus Classification (Linnaeus, [1938]), Universal Decimal Classification (BS 1000M, [1993]). These tend to be general schemes that were primarily developed with libraries in mind. In contrast, however, there is no universally accepted classification for engineering design information, although classifications such as INSPEC [1988], that was developed by the Institution of Electrical Engineers, do exist within the domain of engineering.

A possible reason for this deficiency is that engineering design information is dynamic, and thus difficult to classify without contravening the principles outlined above (Rabins *et al*, [1986]). It may, for example, undergo changes in content or it may change from a bibliographic to a verbal or even a computer based format. Therefore, as noted by Noble [1989], *"library classification and indexing systems are unsuitable for use by engineering designers"*.

Within the 'set' of engineering design information, however, certain distinct types of information, such engineering drawings, may be more amenable to classification than others. Yet, in the absence of guidelines, it is apparent that organisations may have developed systems without adhering to the principles of classification outlined above. For example, Court *et al* [1997b] noted that engineering drawings are often classified by numbering systems (based around job, drawing, or part numbers) that, according to Jack [1989], *"...are not systems at all..."*, and as a consequence they often breakdown and are subsequently replaced by what is usually another invalid system. Little is known, however, about the systems currently used for classifying the standard supplier literature that is stored within engineering organisations; a deficiency that will be addressed in subsequent sections, that present and discuss the results of the author's investigation into the organisation and handling of this information source within a typical engineering organisation.

3.4 Design Information Audit - Background

In order to establish a base-line for the management of standard supplier literature within industry today, an extensive audit of global and personal information pools was undertaken within the engineering design department of a collaborating company. Details of the company, its products, its engineering designers, the nature of the investigation, and the resultant findings are presented in the sections that follow.

3.4.1 Company

The case study was performed within a medium sized Original Equipment Manufacturer (OEM), based in the United Kingdom. This organisation will subsequently be referred to as the OEM.

The OEM, classified by the Standard Industrial Classification (SIC, [1992]) as DL 30.01, was founded in 1983 and, at the time of the investigation, employed around 100 full time staff in the design and manufacture of equipment for the printing industry. Its products ranged from optical scanners through to plate-setters. In the case of the latter, a Bill Of Materials analysis revealed that over 90% of the total number of parts (approximately 9000) were standard components in one form or another. It was therefore considered to be well suited to this aspect of the author's research.

3.4.2 Design Department

The design department within the OEM comprised of fifteen engineering designers, including those who specialised in mechanical, electrical, electro-mechanical, software, mechatronic, and optical design. Each of the engineering designers worked within certain designated areas of an open plan design office; a pictorial representation of this is shown in Figure 3.1.

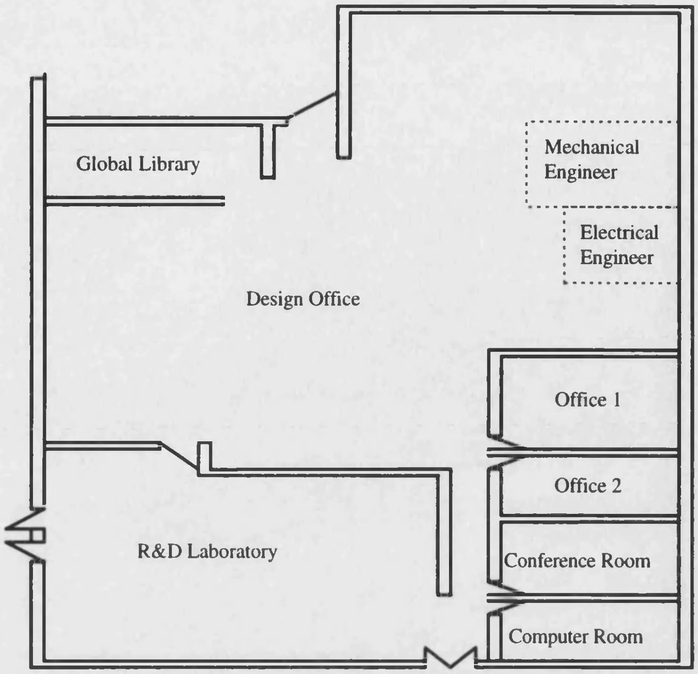

Figure 3.1: Design Office Layout
(Scale ~ 280:1)

Each of the engineering designers had facilities for storing their own 'personal' collection of information along with shared access to a 'global' design information library. The storage mechanisms themselves were none other than bookshelves, filling cabinets, and desk draws; this being typical of many engineering organisations within industry today.

As the purpose of the investigation was to establish how supplier literature was organised and handled within a typical engineering organisation, the information stored within the OEM's global pool along with that stored within two of the engineering designers' personal information pools were targeted. From the range of personal information pools within the design department, a mechanical engineer's and an electrical engineer's were selected, thus also enabling the widely made comparisons to be drawn between these two disciplines (Wilkin, [1981]; Mandel *et al*, [1986]).

3.4.3 Investigation

The investigation was initiated by a semi-structured interview with each engineering designer, regarding personal and global information resources and management procedures. Following the interviews, the three information pools were audited by methodically documenting the following:

- *Information title and supplier name* - for the purposes of establishing whether information items were dual located.

- *Information type* - classified under the following main headings: book, handbook, catalogue, magazine, manual, datasheet, or standard.

- *Information location* - to establish the employed classification and indexing methods along with dual location problem areas.

- *Information age* - to establish how current the information was. In many instances the publication date was the only means of establishing this.

- *Information received date* - to establish how long the information had been retained within the company and how current it was when acquired.

The investigation covered the vast majority of the published information within the various pools and hence included standard supplier literature. The data were then entered into a Microsoft Excel® spreadsheet package to enable analysis and the subsequent production of figures. The results of this, together with a discussion of the main findings and conclusions, are presented in the sections that follow.

3.5 Design Information Audit - Qualitative Findings

This section presents and discuses a number of the key 'qualitative' findings from the investigation, including those that relate to, for example, classification, accuracy, and dual location of supplier literature. The following section presents and discusses a number of the key 'quantitative' findings from the investigation, including those that relate to, for example, age identification and currentness of supplier literature.

A full set of findings, together with the raw data, is available from Boston *et al* [1997c]. Further details may also be found in Boston *et al* [1998b].

3.5.1 Classification Systems within the Global Pool

Supplier literature was stored in two main areas within the global pool and, as outlined below, different classification systems were employed in each instance:

- *Bookshelves* - supplier literature, that included catalogues, handbooks, and datasheets, was sorted in alphabetical order according to the name of the supplier company.
    - ➢ One bookshelf alone housed over one thousand separate items of supplier literature.

- *Filling cabinets* - supplier literature was stored in loose leaf folders that were sorted in alphabetical order according to a classification of 'product types' that had been developed by the OEM.
    - ➢ Within this classification there were approximately 150 categories, such as Active Filters, Cables, Emulators, Fitters-Chips, Heatsinks, etc..

In view of the amount of supplier literature stored within the global pool, the importance of effective classification and coding systems to facilitate information retrieval should be evident. Coding systems were not in-place, however, and the effectiveness of the 'classification systems' employed is also disputable. For example, in the absence of knowledge of what a particular supplier produced, it would be very time consuming for an engineering designer to access information from the bookshelves. Similarly, in the case of the filling cabinets, it was found that many of the supplier catalogues provided information on more than one product area (such as cables *and* heatsinks) and hence the classification system disobeyed the mutual exclusivity principle (Section 3.3.1). This in turn may serve to explain why the engineering designers reported to have spent considerable time trying to retrieve and return information. Further, it is considered that such a system may also have resulted in information being overlooked and created updating difficulties. These are just a few examples of the deficiencies inherent in the classification 'systems' that were employed in the global pool.

3.5.2 Classification Systems within the Personal Pools

Over 65% of the information items within the personal pools were standard supplier literature in one form or another. In general, the classification systems employed were far more 'vague' than those within the global pool. A key factor for this was the number of different types of 'system' that were in operation within each pool, and this in-turn may in-part be attributed to the large number of different information types: trade magazines and journals were stored on bookshelves in order of receipt, with periodic 'culls' taking place when the piles became excessive in size; catalogues, handbooks, and datasheets (the core of standard supplier literature) were stored in a variety of different locations and indexed via a multitude of bespoke classification systems. For example, some were indexed and stored according to their perceived relative importance, others according to design area, project area, state-of-the-art, supplier name, etc..

Despite the haphazard systems employed, it was revealed during interviews that they were reasonably efficient in-terms of information retrieval times. It is considered, however, that this may have been owing to the engineering designers' familiarity with the information stored within their own pools. In-turn, this was attributed to the fact that the relative quantities of information were fairly small and the engineering designers had utilised their personal pools for many years. These 'benefits' though would be nullified during attempts by engineering designers to directly access information from the personal information pools of others. It was noted, however, that this activity was seldom practised, and hence it is unlikely that the value of information maintained within the personal pools was being exploited to its full potential. The sharing of supplier information in general will be further discussed in Chapter 7.

3.5.3 Accuracy of Supplier Literature

Engineering designers frequently utilise information and even design guides provided within standard supplier literature during the course of designing and developing new products (Section 3.2). Owing to the formal nature of this information source, however, it has been noted that engineering designers may perceive it as being accurate (Pitts, [1983]). Yet previous research has indicated that this may not necessarily be the case, as errors are likely (MacCallum, [1986]). For example, Reynard [1991] has reported that books, manuals, journals, and the data and information from materials producers and stockists are of varied quality; and Pitts [1983] noted that standard catalogues often represent products with an aggressive marketing policy, and do not always represent the most appropriate item for the job, both in terms of performance and also cost.

The scope of this investigation did not allow a full assessment of the accuracy of supplier literature to be made, although it was revealed during interviews that this issue had not even been considered. Hence, it was hardly surprising to find that no formal procedures or guidelines existed within the organisation for dealing with this aspect of information management.

3.5.4 Dual Location of Supplier Literature

The dual location of information within engineering organisations is a considerable problem, and one that is highly dependant upon classification. For example, in the case of engineering drawings replacement designs (that may be duplicates or near duplicates of the originals) may be created if systems break down. This may result in, for example, additional maintenance costs, wasted effort, or sub-optimal products, as they may be designed without the benefit of all the available information. These problems also map onto supplier literature where, for example, different editions of the same literature could be located within the engineering and purchasing departments and this may result in discrepancies in product versions and pricing say.

Owing to the multitude of classification schema in existence within the OEM (Sections 3.5.1 and 3.5.2), it is clear that the dual location of supplier literature was a distinct possibility. In fact, the investigation revealed that this was the case, with most duplications occurring between personal pools rather than between the global and personal ones. The scope of the investigation was largely limited to the engineering design department, and hence duplication between other departments was not established. However, in view of the lack of a company wide classification system it is believed that this may have been the case.

3.5.5 Obtaining New Supplier literature

During interviews, it was revealed that no formal procedures were in place within the OEM for obtaining or updating (to be discussed in subsequent sections) supplier literature. As a consequence, when a what was termed 'good' item of supplier literature was obtained (from, for example, a supplier representative, a trade show, or directly from a supplier), it tended to be retained within the engineering designer's own personal pool. Hence, as noted in Section 3.5.2, its value to the OEM as a whole was unlikely to have been exploited to the full. When an engineering designer obtained multiple copies of the same item it would however be distributed amongst the various pools, although it was noted that preference was usually given to the personal pools of the designer's closest colleagues.

3.5.6 Sharing Supplier Literature

As previously noted, the process of sharing supplier literature from the personal information pools with other engineering designers appeared to be relatively poor, and yet this situation was found to be far worse in the context of interdepartmental information sharing. In particular, it was found (although a full investigation of this was not carried out) that copious amounts of the supplier literature maintained within the purchasing department of the OEM were **not** available within the engineering design department. This was found to be a rather sensitive issue within the OEM, and one that appeared to have stemmed from the generally poor links and relationships between the two departments; a repercussion perhaps of the old 'over the wall' style of engineering design, where, in the past, what may be termed 'fairly strong battles' frequently took place between the two departments.

3.6 Design Information Audit - Quantitative Findings

This section details some of the key quantitative findings from the investigation. In particular, it covers issues pertaining to the 'age identification' and 'currentness' of the supplier literature[20] stored within the global and both of the personal information pools.

3.6.1 Age Identification of Supplier Literature

This section addresses issues pertaining to the age identification of the OEM's supplier literature; a prerequisite to establishing whether or not the information was current. In order to facilitate this, the following distinctions were made for each information type (catalogue, handbook, datasheet, etc.) stored within the global and two personal pools:

1. *Percentage that were dated* - this included supplier literature that was published with a date, even if this had been provided by the publisher (publication date) and not the supplier.

2. *Percentage that were date stamped* - this included supplier literature that was stamped with a date of receipt by the OEM.

3. *Percentage that were dated and date stamped* - this included the supplier literature that was in categories 1 *and* 2 above.

4. *Percentage that were un-age-identifiable* - this included all remaining supplier literature that was *not* within categories 1, 2, or 3 above.

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[20] Owing to the different terminology used by suppliers, many classifications of information types would have resulted. Hence, for the purpose of clarity, these had to be rationalised. In addition, the quantity values for some of the information types have been grouped together and displayed on one figure; handbooks and books have been grouped for some of the figures, and in others datasheets, manuals, magazines, and catalogues have been. This decision was based on there being marginal quantities of some information types, and on the similar life expectancy or validity period of others.

The results that emanated from this phase of the research are presented and discussed as follows.

Firstly, as can be seen from Figure 3.2 to Figure 3.4, it is clear that the personal information pools contained a much broader range of information types than the global pool. With regards to this point, interviews with members of the design department revealed a widely held view that supplier literature was often too specialised to be of value to engineering designers working in different fields. Hence, supplier literature was often maintained at a personal rather than a global level. In contrast, however, it was noted in Section 3.5.4 that most supplier literature duplication occurred between the personal pools, and it is thus considered that this view may not be appropriate.

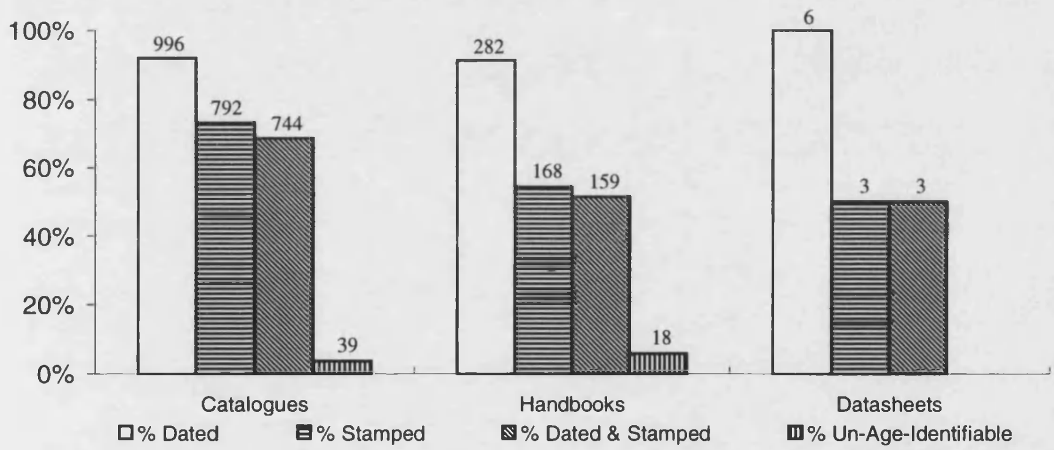


Figure 3.2: % of Information Dating against Type

(Global Pool; quantities shown above columns)

With regards to age identification, it was found that approximately 60% of the catalogues, datasheets, and handbooks stored within the within the global pool had been date stamped. As a consequence, only 10% them, as shown in Figure 3.2, had no means of age identification. Within the personal pools, however, the amount of supplier literature that was un-age-identifiable was much higher[21]. In particular, it can be seen from Figure 3.3 and Figure 3.4 that both catalogues and datasheets within the personal pools were the worst offenders with, for example, more than <u>80%</u> of the mechanical engineer's datasheets having <u>no</u> means of age identification. It is considered that this may be owing to the following two factors:

1. Catalogues and, in particular, datasheets appeared to have a lower percentage of supplier (or publication) dating than all other information types.

2. The stamping of the date-of-receipt on the supplier literature maintained within the personal pools appeared to be lacking.

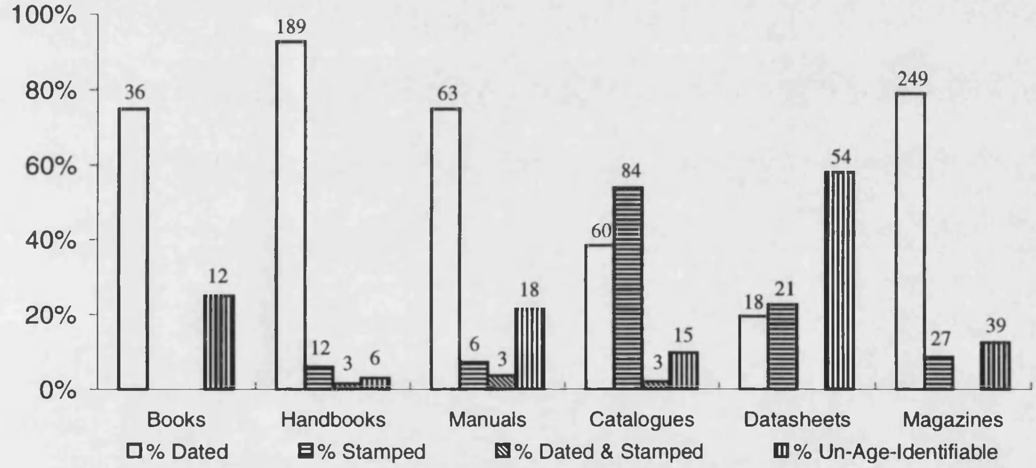


Figure 3.3: % of Information Dating against Type
(Electrical Engineer; quantities shown above columns)

Of note, it can be seen from Figure 3.3 and Figure 3.4 that date stamped supplier literature tended not have a supplier or publication date (low values of '% Dated & Stamped'). In turn, this tends to suggest that the engineering designers were more likely to date stamp supplier literature for their personal pools if it was not already

[21] The catalogues stored within the electrical engineer's personal pool are an exception, as a number of them had been temporarily retained after they had been thrown out of the global pool. The electrical engineer's stated intention was to sort through them before discarding undesired ones.

dated. Hence, it is considered that they may have been conscious of the need to be able to identify the age of supplier literature. More generally, it was found that the level of date stamping was approximately the same within the personal pools, but the overall percentage of supplier literature that could not be age-identified was much higher in the personal pool of the mechanical engineer.

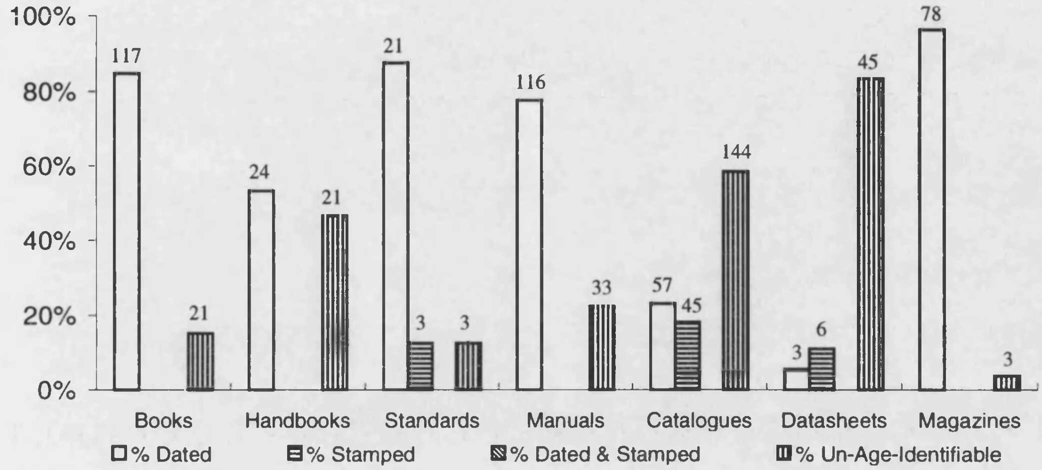


Figure 3.4: % of Information Dating against Type
(Mechanical Engineer; quantities shown above columns)

Finally, when comparing Figure 3.2 with Figure 3.3 and Figure 3.4, it is perhaps strange to note differing levels of supplier or publication dating between the various pools. In particular, the values for the supplier literature maintained within the global pool tended to much higher than those for the personal pools. A possible explanation to this phenomenon is that the information gathered for personal means was of a different nature to that which was gathered for the global pool. Evidence of this was noted previously in this section when discussing the narrow range of information types within the global pool.

3.6.2 Age of Supplier Literature

This section presents some of the key findings pertaining to the currentness of supplier literature maintained within the global and the two personal information pools.

3.6.2.1 Observations on the Global Information Pool

Figure 3.5 and Figure 3.6 show the cumulative percentage of handbooks and catalogues respectively against year of 'publication' for the global pool. Firstly, it can be seen from these figures that supplier literature dates back to approximately 1983. This ties in with the foundation of the company and largely explains the lack of information prior to this date.

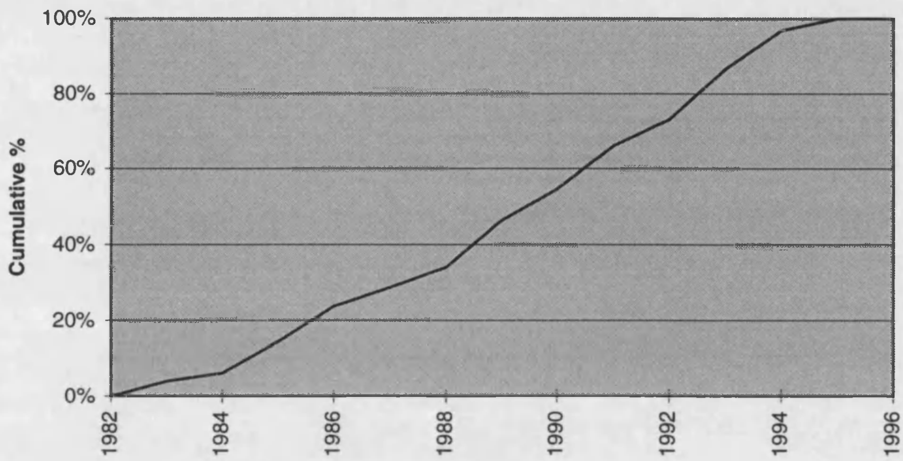


Figure 3.5: Cumulative % of Handbooks
(Global Pool)

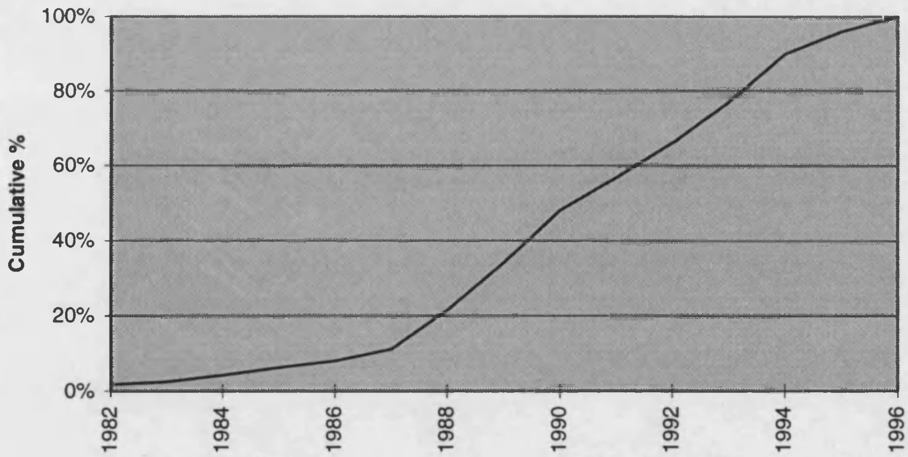


Figure 3.6: Cumulative % of Catalogues
(Global Pool)

From Figure 3.5, it can be seen that the increase in number of handbooks is gradual with year, falling slightly towards the present day. Thus, assuming that approximately the same number of handbooks were acquired each year, this tends to suggests that none, or very few of them, had been discarded.

From Figure 3.6, it can be seen that the cumulative percentage of catalogues follows a slightly different trend to that of the handbooks (Figure 3.5), with a higher percentage of the catalogues existing within a narrower band of years concentrated towards the present day. In particular, when comparing these two figures, it can be seen that approximately 56% of the catalogues are older than 5 years compared to 66% of the handbooks for the same time period.

3.6.2.2 Observations on the Personal Information Pools

The comparative results for the personal information pools are shown in Figure 3.7 to Figure 3.10, and from these it can be seen that the information dates back prior to the foundation of the company. This is indicative of the fact that engineering designers tend to take the information stored within their personal pools with them when they move from company to company. Further evidence of this can be seen in Figure 3.8; it shows a number of distinct steps that were found, as a result of interviews, to coincided with job changes. Hence, each time the engineering designer changed company information relating to a new field was gathered.

Figure 3.7 and Figure 3.8 show the cumulative percentage of books and handbooks against year of 'publication' for the personal pools of the electrical and the mechanical engineer respectively. When comparing these figures to the corresponding one for the global pool (Figure 3.5), it can be seen that the general pattern is the same, and hence re-enforces the notion that handbooks (and books) tend not to be discarded. However, as the information in the personal pools dated back further, the currentness situation was far worse within the personal pools. In particular, these figures show that 80% and 68% of the 'books and handbooks' for the electrical and the mechanical engineer respectively, were older than five years, and this compares to 66% for the global pool.

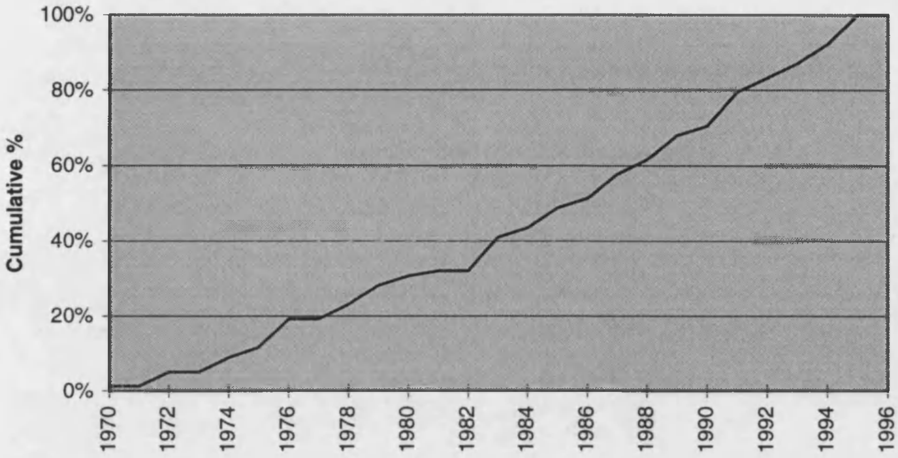


Figure 3.7: Cumulative % of Books and Handbooks (Electrical Engineer)

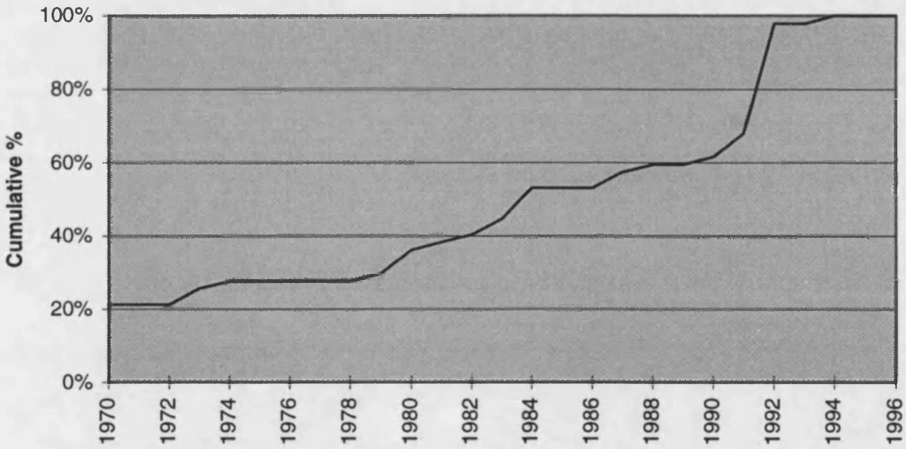


Figure 3.8: Cumulative % of Books and Handbooks (Mechanical Engineer)

Figure 3.9 and Figure 3.10 show the cumulative percentage of datasheets, magazines, and catalogues against year of 'publication' for the personal pools of the electrical and the mechanical engineer respectively.

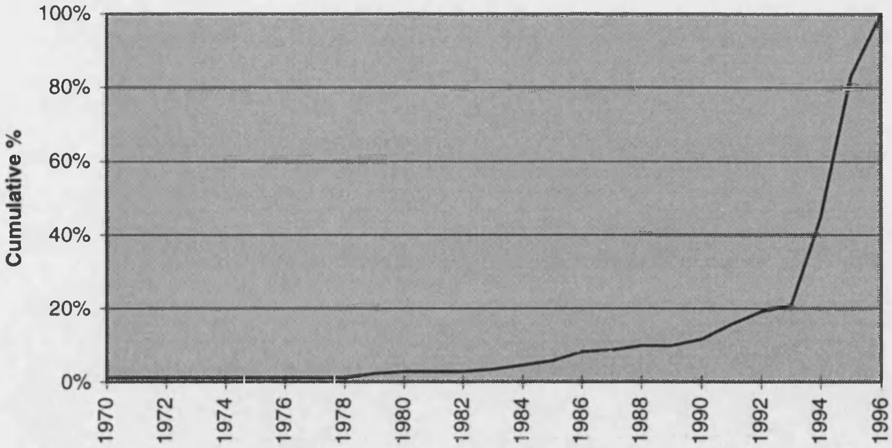


Figure 3.9: Cumulative % of Datasheets, Magazines, and Catalogues (Electrical Engineer)

Again, when comparing these figures to the corresponding one for the global pool (Figure 3.6), it can be seen that the general pattern in information retention for this type of literature is similar. However, within the personal pools a much larger percentage of this information type was from recent years. In particular, for the electrical engineer, less than 16% of this information type was no older than five years, whereas for the mechanical engineer this value was approximately 27%, and comparatively 56% for the global pool.

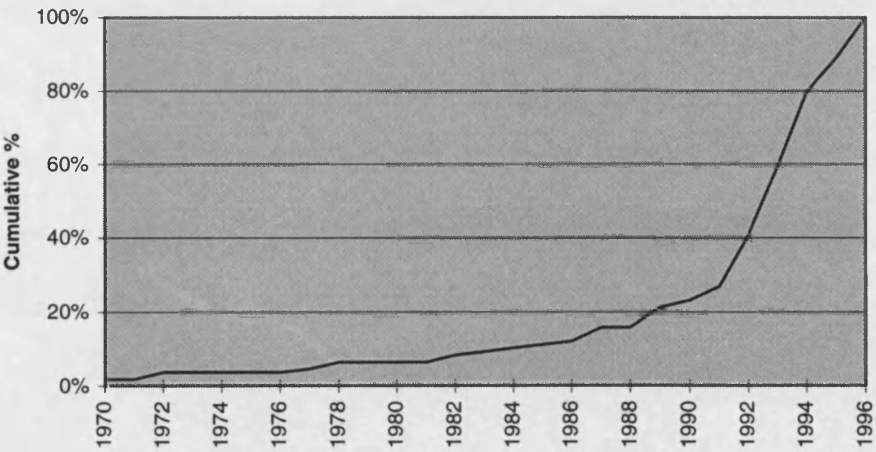


Figure 3.10: Cumulative % of Datasheets, Magazines, and Catalogues (Mechanical Engineer)

3.6.3 Summary

In summary, a number of key points can be drawn from the quantitative findings presented in the previous sections:

1. *Currentness* - handbooks were found to be the most out of date, both within the global and personal information pools. The exact reasons for this are unknown although a number of suggestions can certainly be made:

    - During interviews it became apparent that the engineering designers perceived handbooks to be on a par with books, and as a consequence they were not overly concerned with their age. This was further compounded by the fact that the handbooks seldom contained component prices; it is considered that engineering designers may be more conscious of the age of the information when prices are included.

    - It was noted that many of the handbooks had been purchased. In turn, this may serve to explain the general reluctance to update or even discard them, especially in the case of the personal pools.

    - Supplier literature management procedures were lacking. In particular, no mechanisms were in place to guide the latter phases of supplier literature life-cycle management, namely updating and discarding.

2. *Age identification* - catalogues and in particular datasheets were the most difficult to age identify, especially within the personal pools. Again, the reasons for this may stem from the lack of procedures within the OEM. This issue, however, would not arise in the first instance if suppliers included dates within all of their literature. Their reasons for not doing so may stem from the fact that they want their literature to stay within an organisation for as long as possible, and hence conflicts of interests may be apparent. With regards to this, however, there are arguments for not discarding supplier literature as, for example, it may have value in terms of sparking ideas or providing links to information sources of interest.

Notwithstanding this, the process may need to be monitored and managed with appropriate mechanisms and procedures. A point that will be discussed further in subsequent sections.

3. *General comparisons between the various information pools* - it should be clear from the previous discussions that the personal pools were more current than the global pool. In particular, the electrical engineer's pool was the most current, and this may be a reflection of the turbulent nature of the field, where considerable changes in the state-of-the-art take place on a regular basis. Hence, the electrical engineer tended to scan new literature on a monthly or even weekly basis in order to keep abreast of developments, with the subsequent literature being retained within the personal rather than the global pool. On the whole, however, it is considered that the global pool was better managed than the personal pools; the classification systems were more structured and the supplier literature was more methodically date stamped.

3.7 Design Information Audit - Discussion

This section presents a number of proposals that evolved as a result of the research undertaken. Certain of these are specific to the OEM, whereas others are more general.

3.7.1 Classification

In the short term, it is considered that the OEM may benefit simply by implementing the following proposals:

- Rationalise the number of classification systems in place, both within global and the personal information pools.
  - This may help to, for example, minimise dual location and make the process of updating supplier literature easier.

- Produce a simple list detailing available supplier literature and its location within the organisation (including its loaned status/location).

In the long term, however, it is considered that a company wide supplier literature classification system may be more beneficial. Guidance for this, however, is beyond the scope of this research, although the following suggestions have been proposed:

- Establish the current and (likely) future demands on supplier literature, both within the engineering and purchasing departments.
  - ➢ Due consideration should be given to fact that a number of suppliers are beginning to provide their literature electronically.

- Develop a classification system in line with the principles and guidelines for classification.
  - ➢ This may call for a computer based relational type classification system that points to where the information is located rather than actually storing it. Thus enabling each item of literature to be stored in only one location, but identified from a number of different viewpoints.

- Assign 'ownership' responsibility of the global library to an appropriate individual.

3.7.2 Accuracy

From the discussions in Section 3.5.3, it is evident that engineering designers should exercise a degree of caution when utilising supplier literature. This point has been emphasised by Almli [1988] who noted that there is a need for *tools* and *methods* to evaluate the quality of the information used in product development, and especially collaborative product development; one of the key issues for co-ordination is consistency and integrity of information (Wong and Sirram, [1993]).

The literature was thus consulted with a view to establishing the availability of such tools and methods. This resulted in the identification and subsequent adaptation of a simple quality assurance system[22]. It is considered that this, as outlined below, could form the basis of method to guide organisations in matters of information quality assurance, rather than evaluating the quality of information *per se*:

1. Prior to utilising or relying upon information it is proposed that a design could be evaluated against criteria (Safety, Design Complexity, etc.) such as those shown in Table 3.1; clearly these would need to be tailored or expanded to meet the individual needs of organisations and their products.

2. The resultant values from the design evaluation could be summed in order to produce an overall Rating Value for the design (ranging between 0 and 32 in this instance).

3. This Rating Value could be used in a table, such as that shown in Table 3.2, to calculate a Quality Assurance Level for the design (ranging between I and IV in this instance).

4. The Quality Assurance Level for a design could be used to dictate the extent to which engineering designers were either required to verify the quality of information or allowed to utilise information from certain sources. For example, a Quality Assurance Level of III might require engineering designers to verify information that originates from supplier catalogues but not from handbooks, whereas a Quality Assurance Level of II might require engineering designers to verify information that originates from any source of standard supplier literature.

It should be emphasised that this system is an outline proposal, although it is considered to be worthy of future research attention.

[22] This was adapted from *Guidelines for Quality Assurance in Welding Technology*; produced by the International Institute of Welding (IIW) through its Working Group 'QA in welding technology'. It was developed by them to provide information to organisations developing their quality assurance programmes in compliance with national standards and codes of practice.

Safety		**Manufacturing process complexity**	
No risk to the health and safety of operating personnel	0	Few simple processes required	0
Results in limited risk to the health and safety of operating personnel	3	Significant number of simple processes required	1
Results in significant risk to the health and safety of operating personnel	6	Few complex processes required	2
Results in undue risk to the health and safety of operating personnel and/or limited risk to the public	9	Large number of complex processes required	4
Results in undue risk to the health and safety of operating personnel and to the public	12	**Interfacing component characteristics**	
Design complexity		Interfacing components have no difficult or interrelated characteristics	0
Design effort is minimal and simple	0	Interfacing components have only a few difficult or interrelated characteristics	1
Design effort is significant but simple	1	Interfacing components have some difficult and interrelated characteristics	2
Design effort is significant and presents some complexity	2	Interfacing components have a significant number of difficult and interrelated characteristics	3
Design effort is extensive or complex	3	Interfacing components have a large number of difficult and interrelated characteristics	4
Design effort is extensive and complex	4	**Economics of Failure**	
Design Maturity		Results in negligible inconvenience and/or cost	0
Proven design available	0	Downgrades the service of a facility to a limited extent and results in limited cost	1
Combination of proven design elements for same application available	1	Significantly downgrades the service of a facility and results in significant cost	2
Modification of proven design for a different application	2	Seriously downgrades the service of a facility and results in serious cost	3
Redesign existing item for a different application	3	Results in total loss of service of a facility and extreme cost	4
New design from first principles of a complex item	4		

Table 3.1: Rating of Evaluation Factors

Rating Value Range	*Quality Assurance Level*
18-32	I
11-17	II
04-10	III
00-03	IV

Table 3.2: Value Range to Quality Assurance Level Relationship

3.7.3 Currentness

With a view to providing a metric for supplier literature retention, it was first necessary to consider what was meant by current. The answer to this question was somewhat difficult, however, as a supplier catalogue may contain information that is valid both in the long term and the short term, such as information pertaining to the 'General Theory of Relativity' and the 'Price of Raw Materials' respectively. As a **rough** guideline, however, it has been said that engineering information has a half life of four years; after four years half of it is out of date (Newman, [1995]).

Using the notion of information half life, the following metric for supplier literature retention has been proposed in the form of an equation:

$$\mathrm{p} = \left(\sum_{n=y_0}^{r} \left(\frac{1}{2}\right)^{(y-n)/4} \Big/ \sum_{n=y_0}^{y} \left(\frac{1}{2}\right)^{(y-n)/4} \right) \times 100$$

The terms in this equation are defined as follows:

- p = the ideal maximum percentage of supplier literature that should originate from the years prior to and including the year of interest.
- y_o = the $_1$st year that information was collected within an organisation.
- y = the year that the study or investigation was undertaken.
- r = the year of interest.

Having developed this equation it was then possible to plot an 'ideal' cumulative percentage curve for supplier literature retention; a curve that represents the maximum (in a theoretical sense) percentage of supplier literature that should originate from previous years[23] (anything below this value is of course preferable). An example of such a curve, that uses the following values, is shown in Figure 3.11:

[23] This assumes, for example, that the same amount of information is collected each year. Hence, if none of it had been discarded the 'curve' would appear on the figure as a straight line, stretching from just above the origin to the top right hand corner of the figure.

half life = 4 years; y_o = 1970; and y = 1996. This suggests that no more than approximately 40% of an organisation's supplier literature should be older than 5 years.

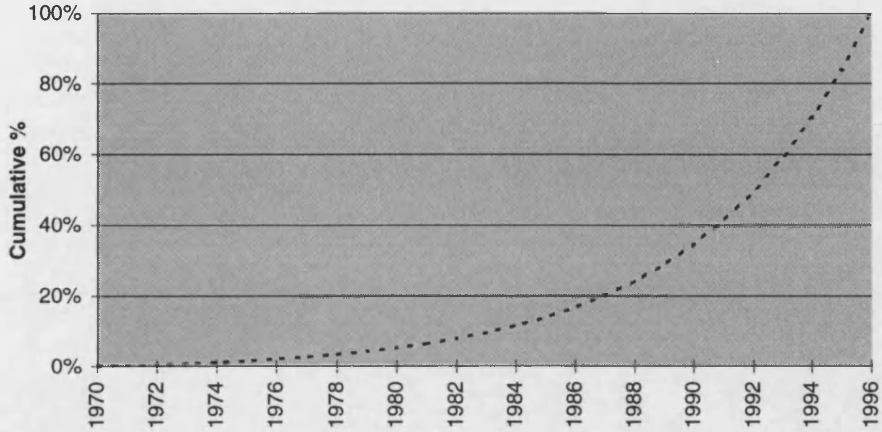


Figure 3.11: An 'Ideal' Cumulative % Curve for Information Retention

With a view to indicating how this metric may be used it has been applied to certain of the results that were presented in Section 3.6.2. For example, by superimposing the curve over that for the cumulative percentage of handbooks stored within the OEM's global library (Figure 3.5) the curve shown in Figure 3.12 is obtained.

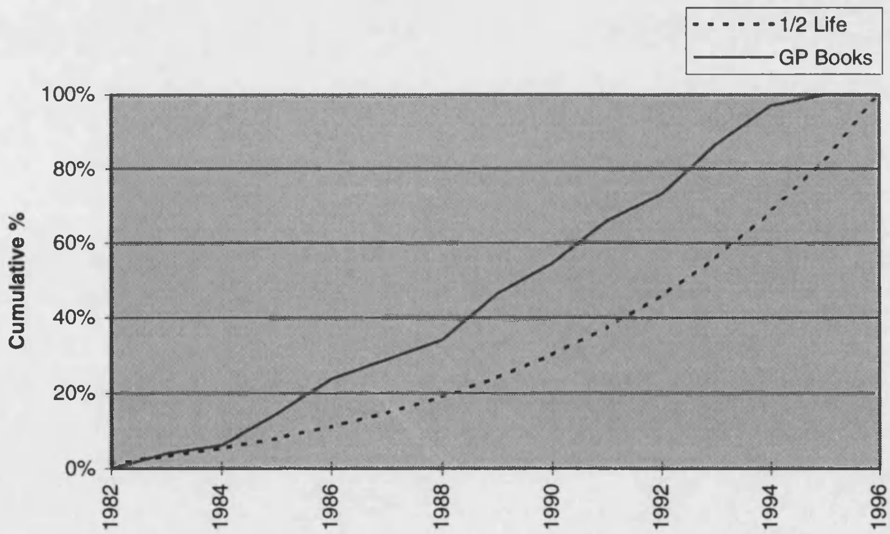


Figure 3.12: A Metric for Handbook Retention in the Global Pool

Similarly, by superimposing it over the cumulative percentage of datasheets, catalogues, and magazines stored within the electrical engineer's pool (Figure 3.9) the curve shown in Figure 3.13 is obtained.

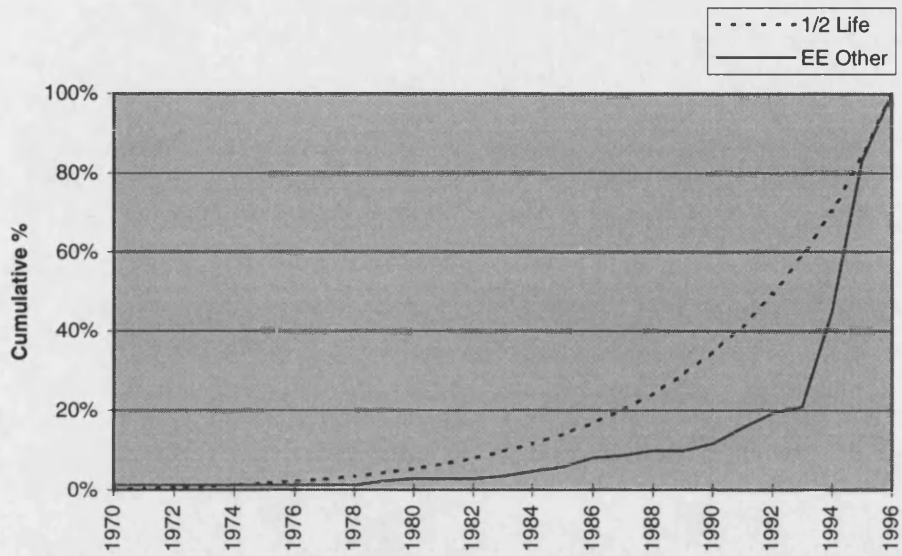


Figure 3.13: A Metric for Catalogue Retention in the Electrical Engineer's Pool

Clearly this metric does not purport to provide a hard and fast rule for information retention; a consequence of the factors and assumptions highlighted previously. Notwithstanding this it does provide an indication of what an acceptable curve might look like. Hence, in this instance, it tends to suggest that the OEM should pay attention to the handbooks within the global pool; the curve is above the metric. However, the currentness of the catalogues within the electrical engineer's pool may be satisfactory; the curve is below the metric.

3.8 Summary

This chapter has highlighted that standard supplier literature, in a wide variety of formats, plays a key role in the preliminary phases of the engineering design process; where decisions and actions have the greatest impact on overall product cost and quality. It has identified a lack of research into how this information source is and how it ought to be managed within industry today. Subsequently, it has presented and discussed the results of an extensive investigation into the organisation and handling of supplier literature within a typical engineering organisation. A number of these findings have been reinvestigated over a broad sample range by way of a questionnaire survey, as detailed in Chapter 7. Finally, it has proposed a number techniques and guidelines that could be used to aid in its management.

More significantly, the research presented within this chapter has gone some way towards verifying initial beliefs that supplier literature may be poorly managed and utilised within industry today (Hypothesis 1). In particular, it was found that classification systems were haphazard and inefficient, information was dual located, the value of information was not being fully exploited, copious volumes of information were un-age-identifiable, a large proportion of the supplier literature retained within the organisation was out-of-date, etc.. In turn, however, this may have been owing to the findings Benyon [1990], who noted that information "*is such a familiar concept that we rarely think about it*".

To this end, it should be emphasised that the utilisation of standard literature is only one means by which supplier information may incorporated within the design and development of new products. Engineering designers are frequently involved in direct and often complex communication and information exchange activities with suppliers. Subsequent chapters of this thesis aim to investigate the issues surrounding these activities in some depth; the second of the author's parallel lines of investigation, as outlined in Section 1.7.

Chapter 4. Modelling Information Interactions

This chapter is primarily concerned with identifying an information modelling technique that is capable of meeting the needs of the author's research. With reference to Figure 1.1, it can be seen that this represents the start of the second of the two parallel lines of investigation.

More specifically, this chapter defines information, distinguishes it from data, knowledge, and communication, and draws attention to factors that impinge upon its value. It provides a background to information modelling and gives an overview of a number of formal techniques that were initially considered to be applicable to the information interactions that take place within and between the design functions of customers and suppliers engaged in product development. Subsequently, it evaluates these techniques against certain criteria that were drawn from the research literature and the needs of this research. Finally, it presents the protocol behind a suitable modelling technique, termed the Multi-functional Information Model (MIM), and provides an example of its applicability to a simple case design project.

4.1 Introduction

The need to study and subsequently understand the engineering design process from an information exchange standpoint such that suppliers can be better integrated was expressed in Chapter 1. This need was further emphasised in Chapter 2, that provided an overview of key areas of design research and the techniques that have been employed to carry it out in the domain. Within this, the significance of information and its communication and co-ordination within the engineering design process and, in particular, the CE design process were highlighted. Yet, at the same time it was noted that these activities are ill organised and poorly understood. This is a consequence perhaps of the fact that much research effort in this area has focused on geometric, functional, and product modelling, rather than on modelling and subsequently understanding the activities associated with, for example, acquiring, utilising, and exchanging information. Moreover, it was noted in Chapter 1 that the available information modelling tools and techniques required to facilitate these investigations may in fact be inappropriate. Thus, as noted in Chapter 1, overcoming this deficiency is not only a key objective of this present research but one that has been expressed by a number of researchers and major research institutions.

Before introducing the concept of information modelling and providing an overview of the currently available techniques, however, a broad vision of information is deemed necessary (Stamper, [1985]). The following section will therefore provide an insight into information from an information theory perspective, with the view to determining precisely what it is and how it relates to knowledge, data, and communication within the domain of engineering design.

4.2 Defining and Distinguishing Information

Information theory was founded in 1949 by Claude Shannon, and in a famous definition he said that ''*information is a message that resolves uncertainty*'' (Shannon and Weaver, [1949]). In considering this definition, however, it tends to imply that a 'message' is only 'information' if it *resolves* uncertainty. Yet, more realistically, it could be said that a 'message' is still 'information' if it *reduces* uncertainty (Rasmussen, [1985]; Rouse, [1986]). In either instance, though, whether or not a message may be classed as information depends upon the individual, and in particular what the individual already knows. Hence, as noted by Rzevski [1985], "*different minds will capture different information from the same source depending on the state of knowledge resident in those minds*".

The understanding of what constitutes information should now be a little clearer, although to define it fully calls for further explanation in order to distinguish it from knowledge, data, and communication; terms that are often used as synonyms.

4.2.1 Information Versus Knowledge

Knowledge, as implied above, is not information; it is much wider concept that is unique to the individual. More precisely, "*knowledge is a state of knowing*" that "*results from mental activity*" (Machlup, [1980]). In the broadest sense it may be considered as the culmination of understanding, instinct, and experiences, that form connected patterns of information within the brain.

Within the context of engineering design, a number of distinct types of knowledge have been identified and subsequently classified by researchers (Devine and Kozlowski, [1995]; Eder, [1989]; Theobald, [1992]; Tomiyama, [1995]; Ullman, [1992a]; Vincenti, [1990]). For example, Ullman [1992a] proposes that engineering designers make use of the three following types of knowledge when undertaking their activities:

- *General knowledge* - gained through everyday experiences and general education. The information used in updating this knowledge is that which people know and apply without regard to the specific domain that they are working in.

- *Domain-specific knowledge* - gained through study and experience within the specific domain that the engineering designer works in.

- *Procedural knowledge* - gained from experience of how to undertake one's tasks within the enterprise concerned. This form of knowledge is often based upon a combination of the previous two.

Within these definitions a further two types of knowledge can be identified, namely, know-how and know-that; Eder [1989] has classified these as prescriptive and descriptive knowledge respectively.

4.2.2 Information Versus Data

The previous sections have established what constitutes information and emphasised that it is not knowledge. Distinguishing it from data, however, is not so straight-forward, as these two terms are commonly used to refer to the same thing. First and foremost, it is worthy of note that data is the plural of datum, and in the modern idiom it is a term frequently employed in the context of computers.

Data are in-fact, as defined by Wilson [1987], "*the representation of information independent of meaning*". They are the raw material upon which information is based, and together with meaning they form information. To emphasise this, if the number 2.718281828459. remains just that to the reader, then it is data, but if the recognises it as the value of 'e', or is informed of this, then it is information. Finally, of great importance to this research are the mechanisms used to share or communicate data, or even information or knowledge. A number of these were discussed in Section 2.4.3, and the aim of the following section is to establish the link between these mechanisms and the various message types as described above.

4.2.3 Information Versus Communication

Communication has been defined by Checkland [1981] as "*the transfer of information*". It is not information in itself, nor is it the transfer of knowledge, as knowledge cannot be transferred directly by one person into another, it must be induced by using information as a stimulus (Ramos, [1986]). This may be depicted graphically, as shown in Figure 4.1, where it can be seen that information begins and ends with knowledge. Its ultimate transfer though may be realised by an ever increasing number of communication solutions.

In order to communicate 'information', however, the 'message' needs to resolve (or even reduce) uncertainty, and in turn this is dependant upon factors such as its accuracy, its currentness, its format, and even the recipient. Therefore, before 'communicating' one must ensure that the 'message' is of *value* to the recipient; an aspect that is covered in some more depth in the following section.

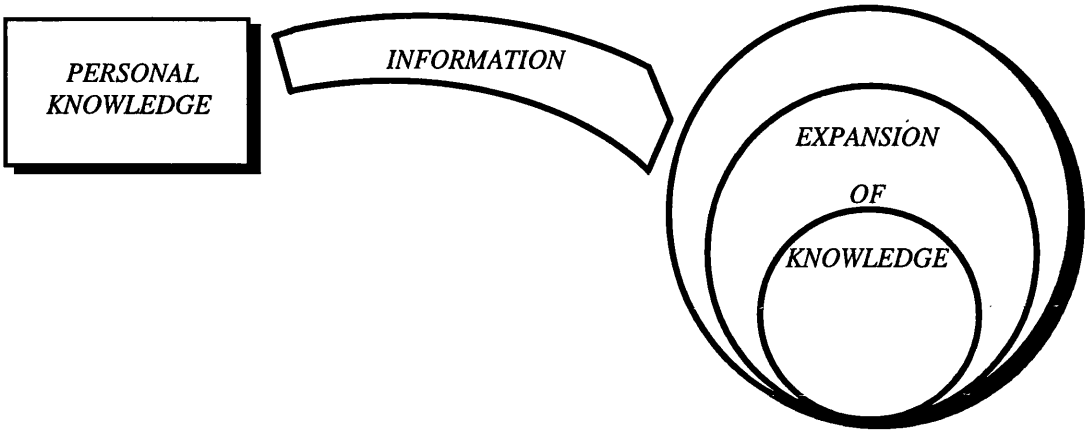


Figure 4.1: The Purpose of Communicating Information (Adapted from Ramos [1986])

4.2.4 The Value of Information

It may be possible to infer from the previous definitions and discussions many of the factors that impinge upon the value of information. Yet the importance of this aspect of information has led to a number of in depth studies by researchers such as Rouse [1986], who concluded that the value of information can be attributed to the following three factors:

1. *It must reduce uncertainty* - by either informing the recipient of something previously unknown or reminding the recipient of something previously known but forgotten.

2. *It must be in an appropriate form* - either it can be in a form that is natural to use or in a form that is transformable.

3. *It must be relevant to the task of interest* - this precludes information that is not yet relevant or about to be relevant, no longer relevant, or categorically irrelevant.

Similarly, Rzevski [1985] talks of the usefulness as opposed to the value of information, that also implies its utilisation, and attributes it to an expanded number of factors. These include relevance, accuracy, currentness, timeliness, location of delivery, media of presentation, format of presentation, control of delivery, and cost. A number of these factors relate directly to information exchange or communication, an important point that has also been raised by Ramos [1986], who stated that:

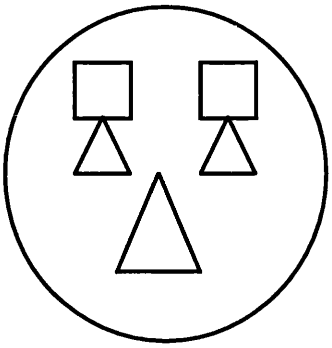
> *"It is impossible to think about what causes the poor utilisation of information without studying the manner in which it has been communicated*".

Again this should serve to emphasise the need to investigate the engineering design process from an information exchange standpoint. The following sections will therefore introduce the concept of information modelling and provide an overview of the formal techniques that are needed for and are potentially suited to such an investigation (Pracht, [1986]; Chadha *et al*, [1991]).

4.3 Formal Modelling Techniques

A model has been described as being a mapping of facts in the real world to a conceptual space (Tomiyama *et al*, [1989]). Models are used continuously by humans in all areas of activity, often without even being aware that they are utilising them. An engineering drawing for example is a type of model, and one that typically represents the physical characteristics of an artefact. This is akin to many models, that tend to represent a simplified view of the world of interest, and thus, as noted by Dieter [1983], this "*...aids in the analysis of a problem*". Further, Chadha *et al* [1991] have noted that the use of models *"...not only helps clarify the current process but also helps in identifying places where the process can be improved"*. Many different types of model exist; each being suited to a particular purpose and constrained by a set of rules pertaining to how they should be constructed. As previously implied, however, this research is concerned with models that are capable of representing the engineering design process from an information perspective.

For example, at a basic level engineering design information (and data or even knowledge) may be considered to reside in either the mind of an individual or within some other storage location. Thus, using this notion it is proposed that a design office could be modelled in terms of 'information sets', as shown pictorially in Figure 4.2; this model represents a design office group consisting of a global design office information set and two individuals, who both have a personal information set.



The knowledge set of an individual, that includes personal memory and experience.

An information set that may be associated with an individual, a group, or a company.

A definable group, that may be an engineering group, a department, or a company.

Figure 4.2: A Conceptual Notion of a Design Office

The above model could be expanded to represent different departments and even companies, with the information flows and interactions between the groups and sets also represented. A simple example is shown in Figure 4.3, and this may serve to emphasise the complexities of information interactions in engineering design. However, it lends little understanding to, for example, the nature and timing of interactions or the types of information that are exchanged during the engineering design process.

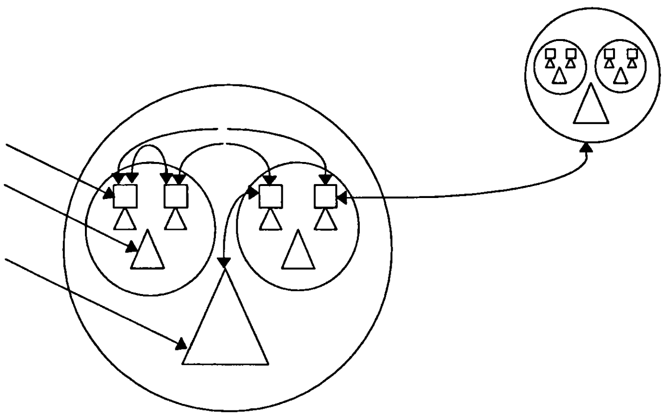


Figure 4.3: A Conceptual Notion of Information Flows

The following sections therefore provide an overview of a number of the formal information and process modelling techniques, and in particular those that were considered to have the potential to meet the needs of this research.

4.3.1 Data Flow Diagrams

Data Flow Diagrams (DFDs) have been used widely for structural analysis of software engineering in recent years, and they are the primary modelling construct in a number of traditional software development methodologies. Their development dates back a couple of decades to the seminal work by DeMarco [1979], who provides a detailed explanation of their development and subsequent use. In general, a DFD describes the functional relationships of the values in a system, including the input values, output values, and data stores. It can represent the flow of data values from their sources in objects through processes that transform them to their destination in other objects. It consists of four basic elements, namely *processes* that transform data, *data flows* that move data, *actor objects* that move and consume data, and *data store objects* that store data passively. These are outlined in more detail as follows:

- *The process* - is a procedural component in the diagram that transforms data values. It was originally represented by a circle or an ellipse but more recently it has been shown as rectangle with rounded corners (Figure 4.4) that contains a description of the transformation (e.g. its name). Each process has a fixed number of input and output data arrows, each of these carries a data value of a given type.

- *The data flow* - connects the output of an object or process to the input of another object or process, and thus it represents an intermediate data value. The direction of data flow is indicated by an arrow that is labelled with a description of the data, usually its name or type. The arrow can also be forked, and this allows the same data value to be sent to several places.

- *The actor object* - effectively drives the DFD by producing or consuming data values. It is represented by a rectangular box or double square that is attached to the inputs and outputs of a DFD. It shows the origin of data (source) used by the system and the ultimate recipient (sink) of data produced by the system. Hence, an actor object is often known as a Terminator.

- *The data store* - is a passive object within the DFD that stores data for later access. It is represented on the DFD as a pair of parallel lines (sometimes joined at one end) with its name written between them. Unlike an actor object, it does not generate any operations on its own but merely responds to requests to either store or access data; the distinction is made by the direction of the arrow that connects it to a process.

An example of a DFD is shown in Figure 4.4, and from this it should be apparent that they are graphic and easy to understand. The DFD does not however show any control information, such as the time at which processes are executed or a decision is made, but it does address a system from the user's viewpoint of data/information.

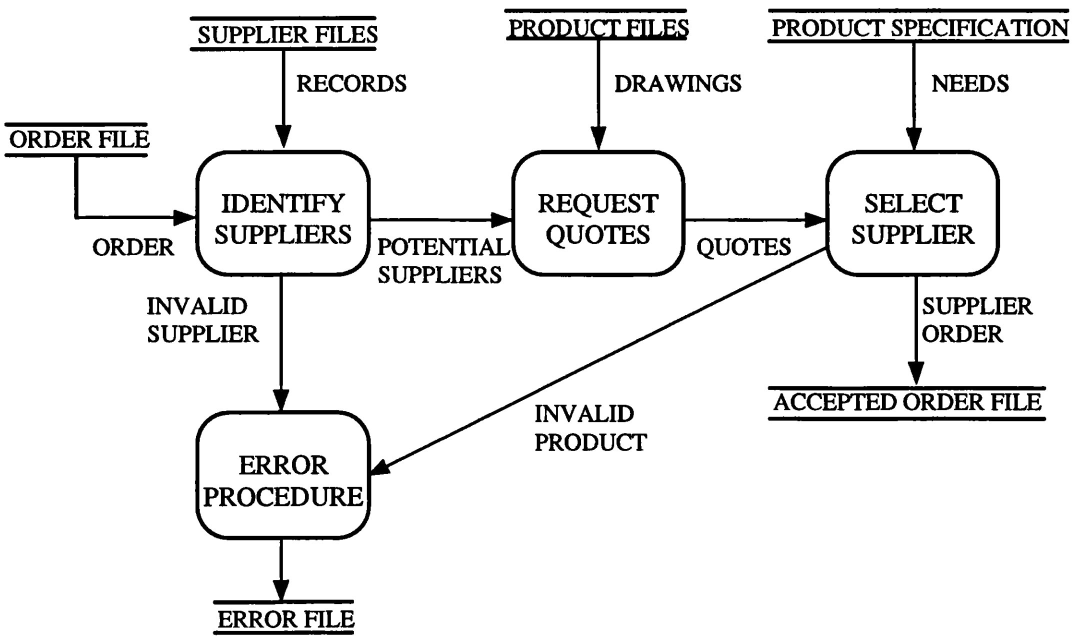


Figure 4.4: An example of a Data Flow Diagram

Other terms commonly used to refer to DFDs include Bubble Charts and Data Flow Graphs.

4.3.2 IDEF Modelling

The US Air force recognised the need for improved modelling techniques to represent manufacturing systems in the 1970's. This recognition was as a direct result of the Integrated Computer Aided Manufacturing (ICAM) program, that aimed to increase manufacturing productivity via the application of computer technology. A major outcome of this work was a family of modelling techniques known as the ICAM DEFINITION (IDEF) methods. In all, there are six different modelling methodologies that target different areas of enterprise modelling, and in particular those associated with manufacturing. The following will provide brief details on those methodologies considered to be relevant to this research, namely IDEF0, IDEF1, and IDEF1X.

4.3.2.1 IDEF0 - Functional Model

IDEF0 was adopted by the US Air Force as a standard project definition (Ross, [1977]). It was derived from the well established graphical language of the Structured Analysis and Design Technique, developed by Ross at Softech Incorporated in the 1970's (Eppinger *et al*, [1990]). IDEF0 is now a widely used modelling tool, that has been employed in the analysis and documentation of the activities and processes found within engineering organisations (Jones and Clark, [1990]; Jazbutis *et al*, [1992]; Chadha *et al*, [1991]; Rangan and Fulton, [1991]).

An IDEF0 model is constructed in a hierarchical manner. Each box on a diagram (see Figure 4.5) represents a process, a function, or an activity, and these can be decomposed to show more detail on subsequent diagrams.

The principle is to gradually reveal more and more detail on successive levels of the model. This is founded upon the notion that the human mind can cope with a great deal of complexity if it is presented gradually in small chunks. The boxes are connected by arrows that represent collections of data or other things. These arrows can branch or merge, but must be laid out in the following strict conventions: the Inputs to a process/function/activity are shown on the left side of the box; the Outputs from a process/function/activity are shown on the right side of the box; the

Controls that constrain or influence a process/function/activity are represented by arrows on the top of the box; and the Mechanisms (sometimes people) that perform the process/function/activity are represented by arrows on the bottom of the box. These conventions are sometimes referred to as ICOMs.

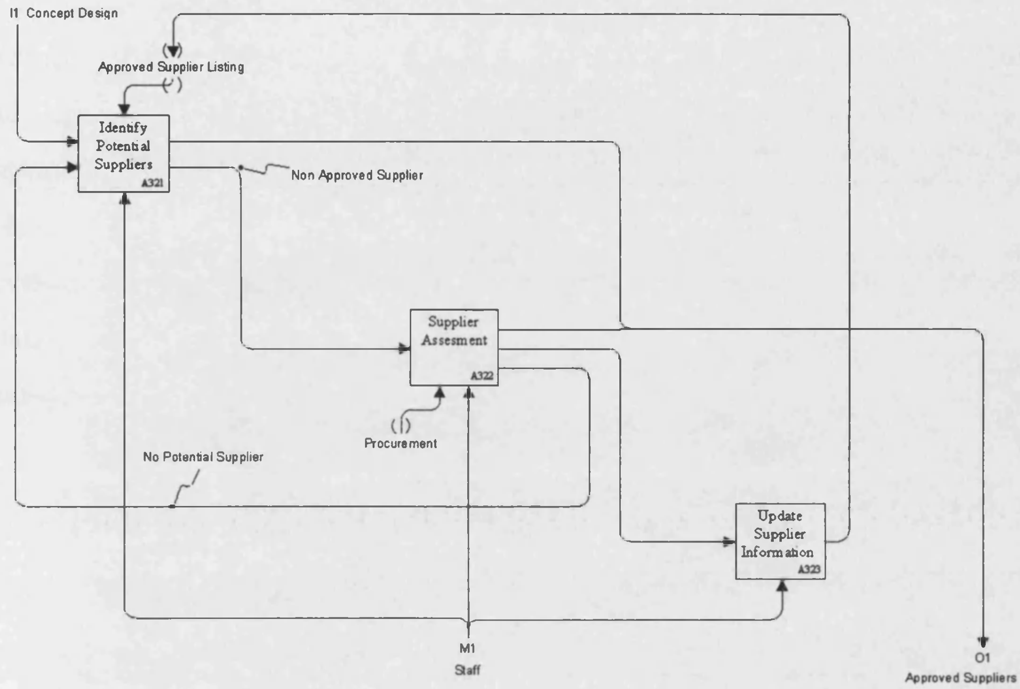


Figure 4.5: An example of an IDEF0 Model

The IDEF0 model is assumed to be static, in that it is intended for modelling systems that consist of discrete activities that transform inputs into outputs. It can describe the process/function/activity and their operation mechanisms within a system, along with control upon them and, to a certain extent, the data. As noted by Jazbutis *et al* [1992], however, they are not particularly good at capturing the flow of data between several activities, and hence they are often used as a complement to other modelling methods and techniques, such as DFDs.

4.3.2.2 IDEF1 and IDEF1X - Information Model

IDEF1 has evolved from a number of techniques, including the entity-relationship model of Chen [1976] and the relational model of Codd [1970]. Unlike IDEF0, IDEF1 is focused towards information rather than process modelling. It was developed as a method to analyse the information associated with an organisation, including its storage, acquisition, and management. Further, Mayer *et al* [1994] have noted that it not only performs the role of an analysis tool, but it also provides an effective mechanism for communicating the information requirements of an organisation.

The need to modify practical applications of the IDEF1 model led to its extension and the subsequent development of the IDEF1X technique, that provides improvements over IDEF1 in a number of areas. These include, for example, enhanced graphical representation, enhanced semantic richness, and simplified development procedures. Akin to IDEF1, IDEF1X consist of entities, attributes, and relationships, including the *has* or *parent-child* relationship between objects. An example of an IDEF1X model is provided in Figure 4.6.

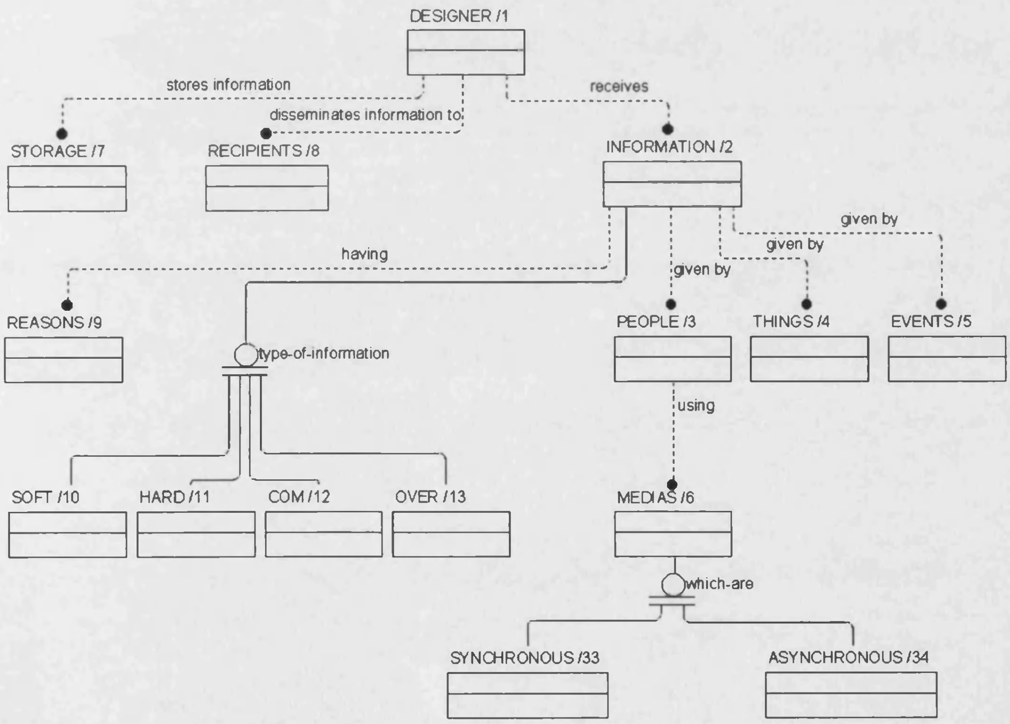


Figure 4.6: An example of an IDEF1X Model

4.3.3 Petri Net Models

Petri Nets were developed by Carl Adam Petri in 1962 (Petri, [1962]), and since then they received considerable attention and enhancements. They were initially developed as a tool to study systems, whereby a system is modelled as a set of mathematical relationships, termed the Petri Net. The Petri Net is often analysed with a view to revealing information on both the structure and dynamic behaviour of a system, and this may then be used as the basis for implementing changes. In recent years, for example, they have been used to aid the automation of manufacturing systems, the design of computer networks, and the assessment of uncertainty in design (Meng, [1995]).

Petri Nets can be used in a hierarchical manner to model systems at multiple levels of detail. They can be represented both algebraically and graphically, although the latter is the most appropriate representation for illustrating the concepts of Petri Net theory. A Petri Net is constructed from the following two node types:

- *Places* (p)- that are represented by a circle.
- *Transitions* (t)- that are represented by a bar.

...and the following two function types, that relate transitions and places:

- *Input* function.
- *Output* function.

The places and transitions are connected by arrows. If the arrow is directed from a place to a transition then the place is defined as an input to the transition, and conversely if the arrow is directed from the transition to the place then it is defined as an output place. Within the Petri Net multiple inputs and outputs are allowed, and these, as shown in Figure 4.7, are represented by multiple arrows.

As previously noted, Petri Nets can be used to model the dynamic behaviour of a system. The implementation of this is controlled by the number and placement of what are termed *tokens*. These tokens, that reside in the *places* (p) (see Figure 4.7), control the execution of the *transitions* (t). If all of the input places to a particular transition contain at least one token, then that particular transition is said to be *enabled*. When enabled, the Petri Net it is capable of execution and the transition of *firing*, as it is termed. When a transition fires, all of the enabling tokens from its input places are removed and all of its output places are distributed with a token, one for each arrow from the transition to the place. Hence, as only enabled transitions can fire, there should never be a situation where a place has a negative number of tokens, termed unmarked. A marked Petri Net means that every place contains zero or more tokens or marks, as they are sometimes called. The *marking* of a Petri Net (μ) is the assignment of tokens to each of the places (p1 to pi), and this is written as a vector. The marking is however likely to change after the firing of each transition, but at any time it represents the state of a system.

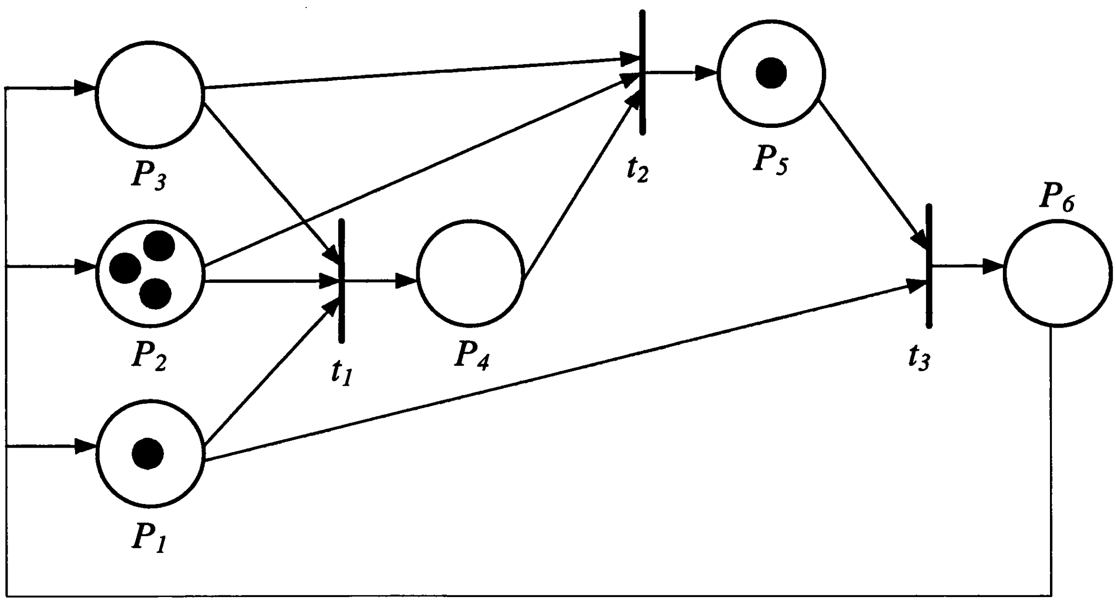


Figure 4.7: An example of a Petri Net

4.3.4 Role Activity Diagrams

Role Activity Diagrams (RADs), that have a formal basis in Petri Net theory, are widely used within the domain of management consultancy (Huckvale and Ould,

[1994]). They were developed by Anatol Holt, at the ITT Company of the USA, for modelling co-ordination in the workplace (Holt *et al*, [1983]). They are primarily concerned with communication, concurrency, and co-operation between interdependent entities, and are often used as a basis for investigation and enaction (Huckvale and Ould, [1994]). The understanding of a system is aided by the graphical representation of a number of concepts, that include roles, activities, goals, and interactions. These are outlined as follows:

Roles - are groups or sets of activities that are generally carried out by an individual or group with the aim of achieving some particular goal. Inherently associated with each role are the resources (such as files, tools, and skills) that are necessary to perform it. Each of the roles in a system co-ordinate with other roles via interactions, although, as indicated by the bounded area in Figure 4.8, they are all independent of each other. A role is typically acted by one person at a time, although the role itself is separate from that person in so much as it could be acted by different people on different days. Hence, roles are not necessarily equated to job titles, as the person fulfilling a title may perform a number of roles or partial roles. Further, roles such as 'expense claimant' may not be equated to a job title and yet they may be performed by anyone.

Activities - are shown on the RAD as a black boxes, and they represent what people or computers do. As Huckvale and Ould [1994] state, the symbolism of the "black box" is intentional, carrying the implication that we are not concerned with how an activity is carried out. These activities, that are usually named with verbs, might include prepare project plan, draw up specification, develop design solution, calculate product cost, produce detail drawings, etc.. Activities are connected to other entities via *state lines*: entering the top of the box is the *pre-state* that the role must reach for the activity to start; emerging from the bottom of the box is the *post-state* that is reached on completion of the activity. Hence, these notions of state allow the definition of a sequence of activities, whereby 'time' proceeds downwards in a RAD.

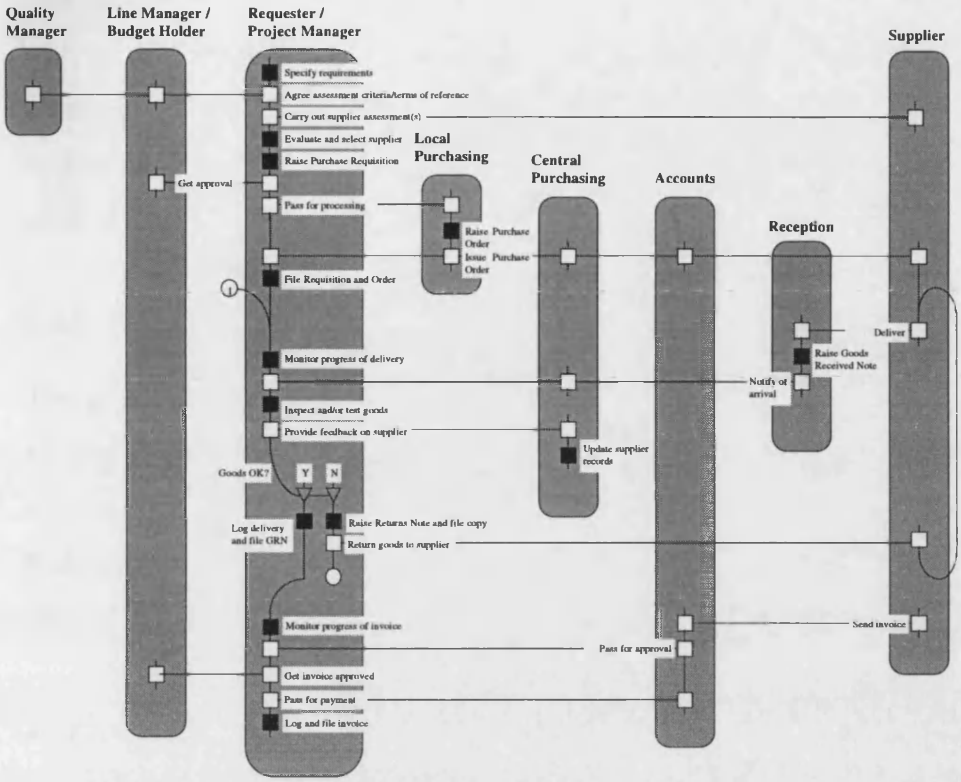


Figure 4.8: An example of a Role Activity Diagram

Goals - are a special case of the more fundamental concept of state, as described above. They may be thought of as states that the processes are trying to reach or achieve. Goals are representative of that which people are actually aiming to achieve in real systems.

Interactions - occur when two or more roles interact. They are represented in the RAD by a white box in each role, connected by an horizontal line. Each of these boxes also has a pre and post state line, the interactions are synchronous, in that they are initiated when both roles are in their pre-states and completed when both roles simultaneously enter their post-states. Interactions often involve the transfer of physical objects, such as drawings, but they may also involve the verbal exchange of information that does not have a physical form.

4.4 Appraisal of Formal Modelling Techniques

The above section has provided an overview of a number of the formal information and process modelling techniques. It still remains to be established, however, whether or not they are capable of meeting the demands and needs of this present research. The following sections therefore aim to establish what these are and hence what characteristics are required from a modelling technique.

4.4.1 Model Requirements for This Research

The primary model requirements were drawn from the hypotheses for this research, as presented in Section 1.6. These include the need for a model to represent *the utilisation and exchange of information* during the engineering design process. Reference to the research literature also led to the identification of a number of additional model requirements. These are outlined as follows:

- *The types and quantities of exchanges* - Christian and Seering [1995] have advocated the need to study the types and quantities of information exchange that take place throughout the design process in order to be able to understand its inter-dependent nature.

- *The design process structure and transformations* - Checkland [1981] has noted that an understanding of a system's behaviour may be gained by studying the structure of the process together with the transformations that take place within it.
  - ➢ Engineering design is a process that consists of a number of distinct phases; information is transformed via these phases from a set of requirements into a set of information that enables an artefact to be realised (Section 2.3). In turn, it is considered that these transformations may be decomposed into a number of information interactions that should be represented within a model.

- *The sequencing of information interactions* - Fox [1994] has emphasised the need to study the order in which activities take place within the engineering design process in order for it to be fully understood.

The perceived requirements for a technique to model the information interactions that take place within and between the design functions of customers and suppliers engaged in product development were drawn from the above. This resulted in the following five criteria that it was considered a model should be capable of representing:

1. The utilisation and the exchange of information.
2. The quantities of information utilised and exchanged.
3. Interactions in the context of the design process.
4. The sequence or timing of information interactions.
5. The impact of information on the design process.

The formal modelling techniques highlighted within this chapter were evaluated against the above criteria, an overview of this is presented in the following section.

4.4.2 Evaluation of the Formal Techniques

Prior to evaluating the formal modelling techniques presented in Section 4.3, case study data pertaining to the information interactions that took place within and between the design functions of customers and suppliers engaged in product development scenarios was collected (see Section 4.6). Subsequently, attempts were made to model this data, using the aforementioned techniques, in line with the criteria outlined above. Examples of the models that resulted from applying these techniques to a particular set of case study data are provided in Boston *et al* [1997d]. During this process a number of general limitations become apparent, and these are summarised as follows:

- They tended to provide snap-shots that were difficult to update dynamically.
- It was difficult to represent design process iterations within the models.
- They did not cope particularly well with the aspect of interaction sequencing.
- They did not support the detail of information exchange and utilisation.
- The completed models were rather difficult to interpret by the non-specialist.

➢ It was difficult to represent interactions in the context of the design process.

Other researchers have also noted similar and additional limitations of the formal techniques during evaluations akin to this, for example:

- Court *et al* [1996], during their attempts to model the information access methods of engineering designers, noted that many of the aforementioned techniques are only capable of modelling continuous processes or systems.
  - ➢ However, information is often accessed in what might appear to be a random manner (Court *et al*, [1996]). Further, the phases of the design process itself may be entered into on an ad-hoc basis (Section 2.3).

- Huckvale and Ould [1994] reported that many of formal techniques have restricted vocabularies and, more significantly, they encounter difficulties representing event sequencing.
  - ➢ However, a good understanding of event sequencing is a pre-requisite to understanding any collaborative process (Fox, [1994]).

- Rangan and Fulton [1991] noted that the majority of the formal techniques were developed primarily for the purposes of modeling static business and administration data.
  - ➢ However, engineering design information tends to be both dynamic and semantically rich (Rabins *et al*, [1986]).

It should be apparent from the above that the formal techniques are not ideally suited to the modelling of engineering design information. Moreover, it was considered that they would require considerable modification in order to overcome the previously noted limitations (if at all possible) such they could meet the criteria laid down in Section 4.4.1. A decision was therefore made to develop a new 'tailor made' technique for modelling the information interactions that take place within and between the design functions of customers and suppliers engaged in product development. This, as described in subsequent sections of this chapter, has been termed the Multi-functional Information Model (MIM).

4.5 The Multi-functional Information Model

The following section highlights the considerations that were made prior to conceiving the MIM, and subsequent sections provide the protocol behind it and highlight its representational capabilities.

4.5.1 Outline Requirements for the Model

Primarily, it was intended that the MIM should be capable of both meeting the criteria highlighted in Section 4.4.1 and overcoming the majority of the deficiencies found within the formal modelling techniques during their evaluation (Section 4.4.2). Furthermore, it was considered that the MIM should not only serve the purpose of an analysis tool but it should also facilitate the communication of new suggestions and ideas. Hence, it was believed that it should be capable of representing 'synthetics', or suggested ideal information interactions, and thus serve the purpose of both a descriptive and prescriptive modelling tool.

In addition to the above, reference to the related modelling literature resulted in the identification of a number of attributes that Martin and McClure [1985] have used to characterise what they consider to be a *"good model"*. These, as outlined below, together with the protocol behind the formal modelling techniques, were used to guide the development of the MIM:

- Be an aid to clear thinking.
- Be computer manipulatable.
- Be readable by end users.
- Have a consistent notation.

Parallels can be drawn between the above and those principles laid down for the development of classification and coding systems (Section 3.3.1). In particular, the principle of the 'user's viewpoint'[24] can be likened to the third of the above points and in some respects to even the first and the fourth. Hence, in order to facilitate the

[24] Development should be directed from the perspective of the user and not the developer.

involvement of engineering designers in both the construction and the analysis of models[25], it was deemed necessary to develop and validate the MIM within an industrial context.

The attainment of the above requirements and objectives will be discussed within the following sections, that present the protocol behind the MIM and outline its representational capabilities. Further details will also be provided in subsequent chapters.

4.5.2 Customer-Supplier Representation in the MIM

With reference to the aims and objectives of this research, as highlighted in Section 1.6, it should be apparent that it is focused towards integrating the information (and knowledge) available from suppliers into the engineering design process.

In view of the above it was believed that the model should represent both a customer and a supplier in a unified symbolic manner. This has been achieved by representing the two parties with semicircles that join to make the complete model, as shown in Figure 4.9.

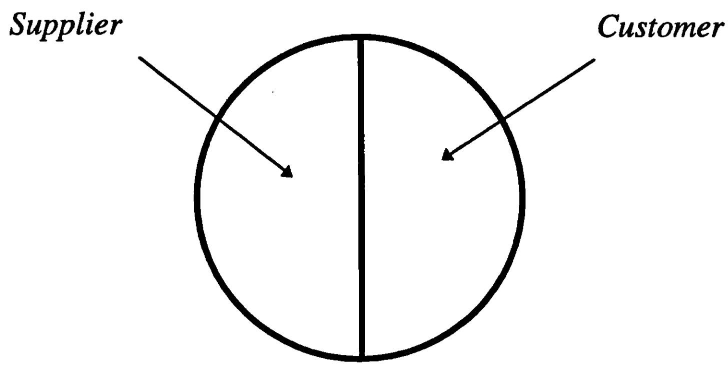


Figure 4.9: Representing Customer and Supplier Halves in the MIM

[25] This is considered to be an important point; Huckvale and Ould [1994] noted that the benefits from modelling often accrue to the modeller and not the model analyst.

4.5.3 Design Process and Information Type Representation in the MIM

The engineering design process is made up of a number of phases, during which distinct activities and information interactions take place (Section 2.3). It was therefore thought to be appropriate to centre the MIM around these phases, and a decision was therefore required as to which definitions of the design process phases to utilise.

As noted in Section 2.3, the design process model presented by Pahl and Beitz [1984] is highly respected within the design research community, and hence a decision was made to utilise the phases defined in their model within the MIM. For the purposes of this research, however, it was felt this classification needed to be extended to take into account phases beyond the detail design phases. This was because the collected case study data suggested that a significant number of information interactions may take place between the customer and the supplier within these phases and, in certain circumstances, these may lead to design process iterations.

As shown in Figure 4.10, the areas between the rings in the MIM correspond to the following phases in the engineering design process, with which a particular information interaction may be associated: Need, Concept, Embodiment, Detail, Prefabrication, and Test.

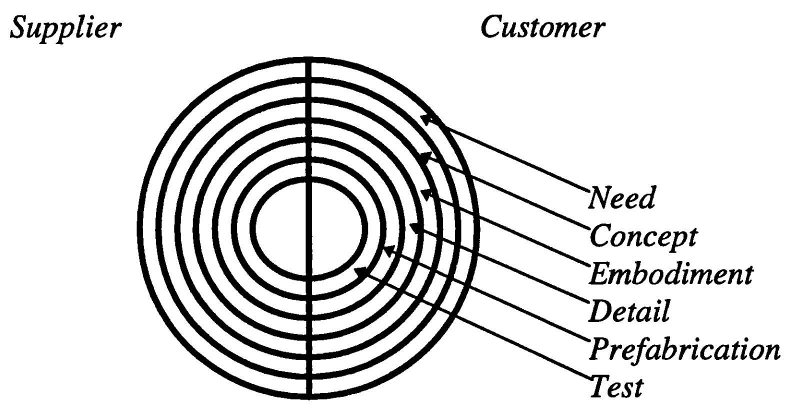


Figure 4.10: Representing Information Types in the MIM

It should be emphasised that any other design process classification could be used within the MIM, or the phases could be numerically classified or specified such that they tie in with a company's own procedures.

4.5.4 Representing Information Interactions in the MIM

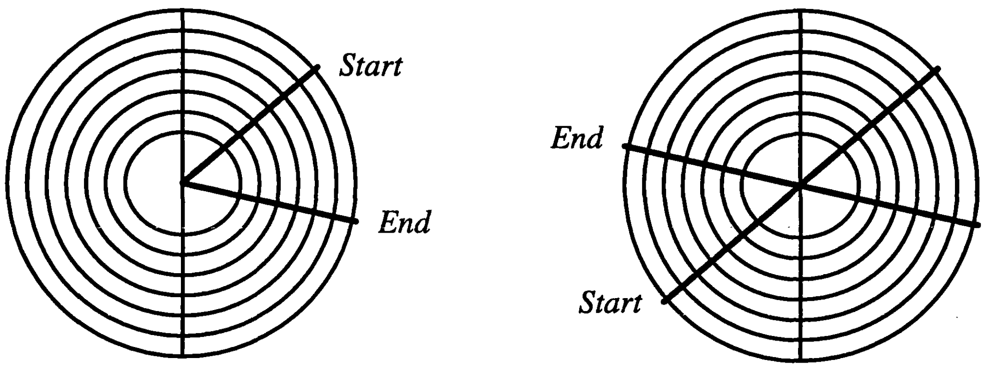
As shown in Figure 4.11a, information interactions are bounded by pairs of lines within the MIM. The first line represents the start of an interaction and the second line represents the end of an interaction; an interaction may, for example, be a communication with a supplier or the accessing of information. Furthermore, two key types of interaction are differentiated within the MIM, namely, those not involving both parties and those involving both parties (typically *the* customer <u>and</u> *the* supplier). These are outlined as follows:

- *Indirect* - the lines that bound this information interaction (start & end) are shown only on the side of the model that represents the party that is directly involved with it. For example, if the customer received a fax from a 3rd party, or if information was accessed from within the confines of the organisation, then the two lines, that meet at the centre of the model, would be represented on the customer's half of the model, as shown in Figure 4.11a.

- *Direct* - the lines that bound this information interaction (start & end) pass through the centre of the model, and hence are shown on both sides. This, as shown in Figure 4.11b, serves to emphasise the fact that both parties were involved in the interaction, whereby this may have been, for example, a telephone conversation, a fax, or a meeting.

By employing different line types within the model (dotted, dashed, dash-dot, etc.) the notion of distinguishing between different types of information interaction could be extended in order to represent, for example, the specific types of communication media used (fax, verbal, letter, etc.). However, in order to comply with the *'be an aid to clear thinking'* requirement (Section 4.5.1) these ideas were not employed; it was believed that the distinction made portrays sufficient information to the user of the

MIM, whilst at the same time minimising the clutter of added line types that may portray information of less value.



a: Indirect Interactions **b: Direct Interactions**

Figure 4.11a & b: Representing Interaction Lines in the MIM

4.5.5 Information Representation in the MIM

Within the MIM, an information item (or items) that relates to a particular interaction is represented by a node (or nodes) between the appropriate interaction lines (as described above). This is shown in Figure 4.12.

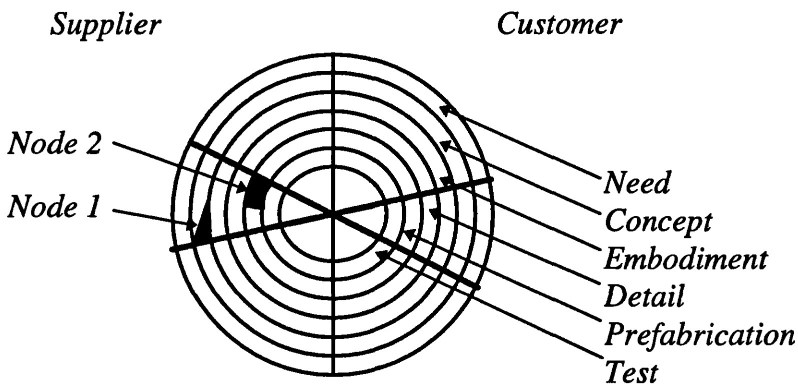


Figure 4.12: Distinguishing Information in the MIM

The radial position of a node corresponds to the phase of the product life-cycle with which the item of information it represents is associated. Furthermore, the use of half and full nodes[26] enables a distinction to be made between those information items that have been received (*Node 1*) and those information items that have been created (*Node 2*) respectively.

4.5.6 Time Representation in the MIM

Within the MIM, clockwise rotation relates to event sequencing (the order in which information interactions take place). To explain, Point A in Figure 4.13 is both the start point of the project for the customer and the end point of the project for the supplier. Likewise, Point B is both the end point of project for the customer and the start point of the project for the supplier. Point Y is thus some point in time between the start and end of the project from the customer's perspective, and point X is that same point in time from the supplier's perspective. Therefore, line XY represents the same point in time for both the customer and the supplier.

Using the above notation the MIM is thus capable of representing the order in which activities are undertaken. Hence it may be able to cope with issues pertaining to co-ordination and concurrency in the engineering design process. For example, in Figure 4.12 the supplier received the information relating to the concept phase of the product life-cycle (*Node 1*) immediately before creating the information relating to the prefabrication phase (*Node 2*).

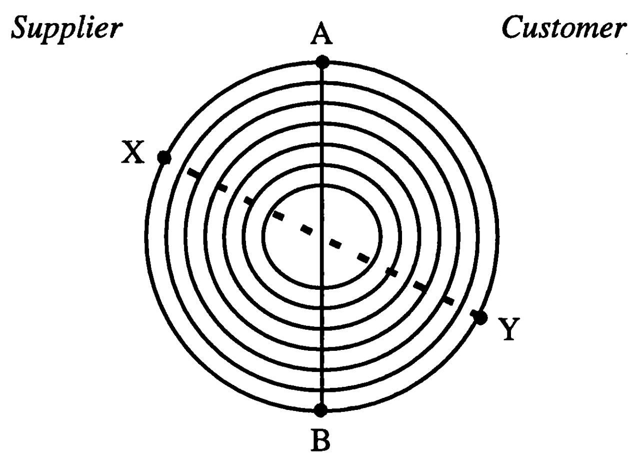


Figure 4.13: Distinguishing the Order of Activities in the MIM

[26] Within PIMS, the software implemented version of the MIM (to be discussed in Chapter 5), this distinction is made by the use of colour and not node shapes.

Further, depending on how the MIM is constructed it can represent not only the order in which activities were undertaken, but also the exact time at which they were performed. To achieve this the information nodes and interaction lines need to be configured in relation to the *degree* of clockwise rotation, such that 1 degree corresponds to a particular increment of time.

4.5.7 Example Application of the MIM

It is considered that a more comprehensible understanding of the MIM and its representational capabilities can perhaps be best achieved by way of an example. It has therefore been applied to the information interactions that took place in a simplified case design project. This involved the design (customer) and manufacture (supplier) of a roller spindle that formed part of a vehicle suspension system 'bump stop'. As a result of information obtained from the supplier, the original spindle design (Figure 4.14) was modified on a number of occasions.

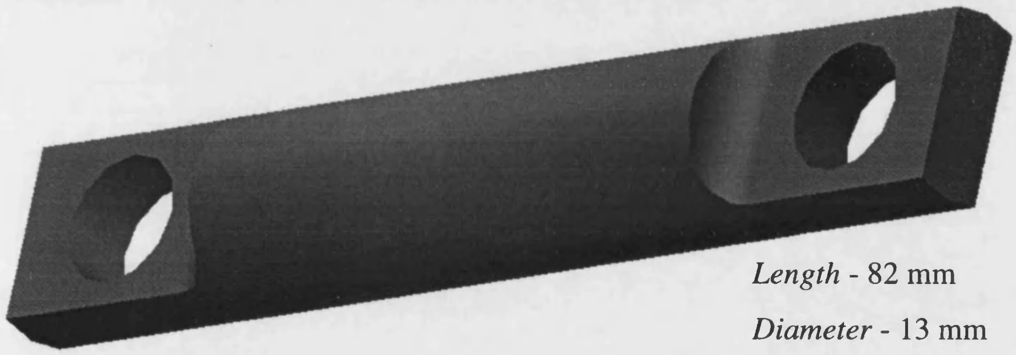
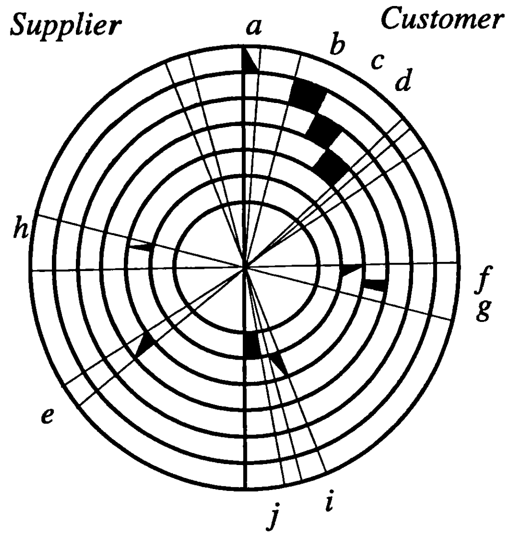


Figure 4.14: Original Roller Spindle Design

The MIM model for the case design project (Figure 4.15), that includes one of the aforementioned design process iterations, is displayed in a *'Time Linear'* mode and thus the angular positions of the nodes are proportional to time. It represents a simplified set of the information interactions that took place from the initial need through to testing of the artefact after manufacture. The model rings correspond to the phases in the engineering design process as described in Section 4.5.3, and the letters adjacent to the nodes correspond to the following brief descriptions:

a: Customer received a set of requirements for a new roller spindle.
b: Customer created and then selected the concept spindle design.
c: Customer checked the dimensions and produced detail drawings.
d: Customer finalised the spindle design and then had it checked.
e: Supplier was faxed detail drawings with delivery requirements.
f: Supplier suggested changing diameter tolerance to a standard one.
g: Customer checked detail drawings and changed the detail design.
h: Supplier was informed that the tolerance change was acceptable.
i: The batch of new roller spindles was delivered to the Customer.
j: Customer tested a spindle and confirmed that it was acceptable.



KEY

Ring No.	Phase
1	Need
2	Concept
3	Embodiment
4	Detail
5	Pre-fabrication
6	Test

Full Node } Created Information

Half Node } Received Information

Figure 4.15: Application of the MIM to a Simple Case Study

With reference to Figure 4.15 it can be seen that a number of information interactions took place within and between the customer and the supplier. For example, during one of the direct (and in-fact synchronous) information interactions, three items of information were involved:

➢ *Node f* - this is half node, which means that information was received during the information interaction. It is on the customer's side of the model, which means that the customer received it. It is in the fifth ring, which means that it was information relating to the prefabrication phase of the product life-cycle.

➢ *Node g* - this is a full node, which means that information was created during the information interaction. Again, it is on the customer's side of the model, which means that the customer created it. It is in the fourth ring, which means that it was information relating to the detail phase of the product life-cycle.

➢ *Node h* - this is a half node, which means that information was received during the information interaction. It is on the supplier's side of the model, which means that the supplier received it. It is in the fifth ring, which means that it was information relating to the prefabrication phase of the product life-cycle.

Preliminary findings that resulted from the application of the MIM to a number of case design projects, together with an overview of the case study data collection methodologies employed, are presented in the following section.

4.6 Preliminary Applications of the MIM

Having developed the MIM it was then used to model case study data pertaining to the information interactions that took place within and between the design functions of customers and suppliers engaged in various product development scenarios (Hypothesis 2). This resulted in a number of MIM models (such as those presented in Figure 4.15 and Boston *et al* [1996]) that, in the first instance, were analysed with a view to establishing whether the technique was capable of meeting the needs of this research. In turn, this resulted in a number of significant insights, as outlined below:

1. An improved understanding of this area was gained and a number of key observations were made (see Chapter 6).

- These suggested that information available directly from suppliers, as opposed to indirectly via standard supplier literature (Chapter 3), was also under-utilised by engineering designers today (Hypothesis 1).

2. The MIM technique could be extended in order to better represent the information interactions that took place (see Chapter 5).
   - Distinctions were made solely between received and created information within the MIM models. It was apparent from the case study data, however, that this concept needed to be extended somewhat.

3. Analysis of the MIM models indicated that the collected case study data may not have been sufficiently complete.
   - Initially it was considered that these 'gaps' were solely owing to the designers' use of memory. As outlined below, however, it was apparent that the employed data collection methodologies may have been at fault.

Within Section 2.2.4 it was noted that the research techniques commonly employed within the domain of engineering design are either unsuitable or have not previously been applied in a manner akin to that required for this research. Hence, tools and guidance to aid the collection of the desired empirical data were not initially readily available.

The above points are emphasised by the fact that empirically based research within the domain has not been widespread (Stauffer and Ullman, [1988]). Further, and of particular significance to this present research, it has been noted that communications of an informal nature have seldom been studied within the domain (Rangan and Fulton, [1991]; Sonnenwald, [1996]). Their capture, however, was seen to be fundamental to the overall success of this research; a point that is emphasised by Eppinger *et al* [1990] who noted (in the context of engineering design as it is carried out in practice) that they are *"undeniably essential to project success"*.

Initial case study data collection methodologies employed within this research were largely reliant upon the engineering designers recording their information interactions[27]. Yet, from analysing the MIM models and subsequently interviewing those parties involved, it became apparent that certain data, including that pertaining to informal communications, had not been recorded. It was considered that this may have been owing to many factors, for example, Safoutin and Thurston [1993] have noted that the importance of information *"...might not be obvious if the information does not travel along observable communication channels"*. Hence, it was plausible that the engineering designers may not have realised the need or even forgotten to document certain of the required case study data.

It was thus clear, even though some headway had been made towards addressing Hypotheses 1 and 2, that in order to progress this research a tool or methodology would be required to facilitate the capture of case study data. This, as outlined in Chapter 5, was achieved by developing the Product Information Modelling System (PIMS); a software package that integrates an extended version of the MIM technique with various new classification schema.

4.7 Summary

This chapter has provided an insight into information from an information theory perspective, and in so doing distinguished it from data, knowledge, and communication; terms that are often used as synonyms. Having therefore presented the basic theory behind customer-supplier information interactions, an overview was provided of a number of the formal information modelling techniques, that it was initially thought could be employed to facilitate the desired understanding of these interactions.

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[27] Each of the engineering designers was interviewed with a view to explaining the nature of this area of the research and gaining a general understanding of their day-to-day activities and the procedures adopted within their companies. Subsequently, for each case design project, they were requested to document the following: details of the communication media employed, the timing of information interactions, copies of all the *formal* documents that were both utilised and exchanged (e.g. PDSs, order forms, drawings, etc.), and, finally, details pertaining to *informal* information. The case studies were also backed-up by documenting them from the perspective of the other organisation (the supplier in most instances), and, where possible, such as during meetings, the author also undertook the process of data recording.

During the evaluation of these techniques, however, it was revealed that they were unable to address the needs of this research. Subsequently, a decision was made to embark upon the development of a new technique for modelling the information interactions within and between the design functions of customers and suppliers engaged in product development. Details of this technique, termed the Multi-functional Information Model (MIM), including its representational capabilities, the protocol behind, and an overview of its application to a simple case design project were also provided within this chapter.

Finally, an overview was provided of the methodologies employed in the collection of case study data and the insights that were gained as a result of preliminary applications of the MIM to this data. Significantly, it was noted that the MIM technique could be expanded in order to better meet the needs of this research and, of further significance, a tool or methodology was required to overcome case study data collection difficulties. The attainment of these objectives will be covered in Chapter 5, that presents both the development and an evaluation of PIMS; in line with the criteria that were drawn up for evaluating the formal information modelling techniques (Section 4.4.1).

Chapter 5. The Product Information Modelling System

This chapter continues with the information modelling theme of the previous chapter. It outlines the development and highlights salient features of a software package termed the Product Information Modelling System (PIMS). PIMS is a quasi-quantitative dynamic information modelling solution that evolved from the integration of various classification schema with an extended version of the MIM technique (Section 4.5). It was developed in a manner that would enable it to be utilised by engineering designers to collect and simultaneously model case study data in an industrial context. This implementation together with the resultant observations and findings are detailed in Chapter 6.

5.1 Introduction

Within Section 4.6 it was noted that the collection of case study data, pertaining to the information interactions within and between the design functions of customers and suppliers engaged in product development, was frustrated by a lack of suitable data collection tools and methodologies. It was believed, however, that this deficiency could be overcome by developing a software package that integrated an expanded version of the MIM technique with various new classification schema. Further, by developing such a system it was considered that the capabilities of the MIM technique could be extended to levels that would be unattainable with manual paper-based modelling.

The proposed features of such a system are outlined as follows:

- *An input interface* - that prompts the user to enter all the necessary (information interaction related) data to enable succinct models to be built.

- *A database* - that stores inputted data and thus enables it to be reused and hence entered in 'real time' as more information is known about a design project.

- *A model interface* - where models that are built automatically by the system (from data stored in a database) may be viewed and updated dynamically.

- *Increased functionality* - to enable excessive detail to be obscured or the models to be viewed from different viewpoints at the 'touch of a button'.

- *Enhanced visual representation* - computer-based systems facilitate easy use of colour; this may encourage use of the system and enhance the interpretation and understanding of the models.
  - ➢ Marcus [1991] has noted that 'colour' is not only superior to 'black and white' for communicating concepts and aiding understanding, but is also more enjoyable to use.

The above list is certainly not exhaustive and yet it clearly indicates the potential benefits of such a system. Moreover, it was believed that such a system could be implemented in industry and subsequently used by engineering designers to record design information interactions as and when they took place. In turn, it was considered that this could help to overcome the aforementioned data collection difficulties and also enable a larger number of case studies to be undertaken. Further, owing to the direct involvement of the engineering designers in the model building process, it was believed that they would be in better position to aid in the data verification, model validation, and analysis phases of this research.

Having made a decision to put these ideas into practice a new research vehicle termed the Product Information Modelling System (PIMS) was developed. Subsequent sections provide an overview of the data storage structure in PIMS; highlight its salient functions and features; outline the extensions that were made to the MIM technique itself; and provide an evaluation of PIMS in line with the criteria that were drawn up in Section 4.4.1. Details pertaining to the utilisation of PIMS within industry and the observations that emanated from analysing the resultant models will be provided within the following chapter, Chapter 6.

5.2 Data Storage Structure

When developing PIMS, initial efforts were focused on selecting an appropriate database and defining a data storage structure.

The need to build models of differing size and complexity resulted in the need for an easily expandable database. A relational database was therefore sought and the Microsoft® Jet® engine selected. This was largely owing to its compatibility with Microsoft® Access®; a proven database management system.

A modular data storage structure was utilised such that each project would have its own database; and each project database contains the following three tables, as shown in Figure 5.1:

1. *Background* - this table contains project overview details, together with preferences such as display window positions.

2. *Set-up* - this table contains an information classification that is defined by the user on setting up a new project.

3. *Values* - this table contains all of the inputted project data. Certain of this relates to the user definable classification stored in the 'Set-up' table.

The last key stage in designing the database was to fully define the fields that constitute each of the tables outlined above. This was accomplished by establishing the data types required to construct models using the MIM technique, make extensions to the MIM technique, and to incorporate additional features within PIMS. The final set of fields are represented within the tables shown in Figure 5.1. It should be noted that the database structure is such that these could easily be expanded if required.

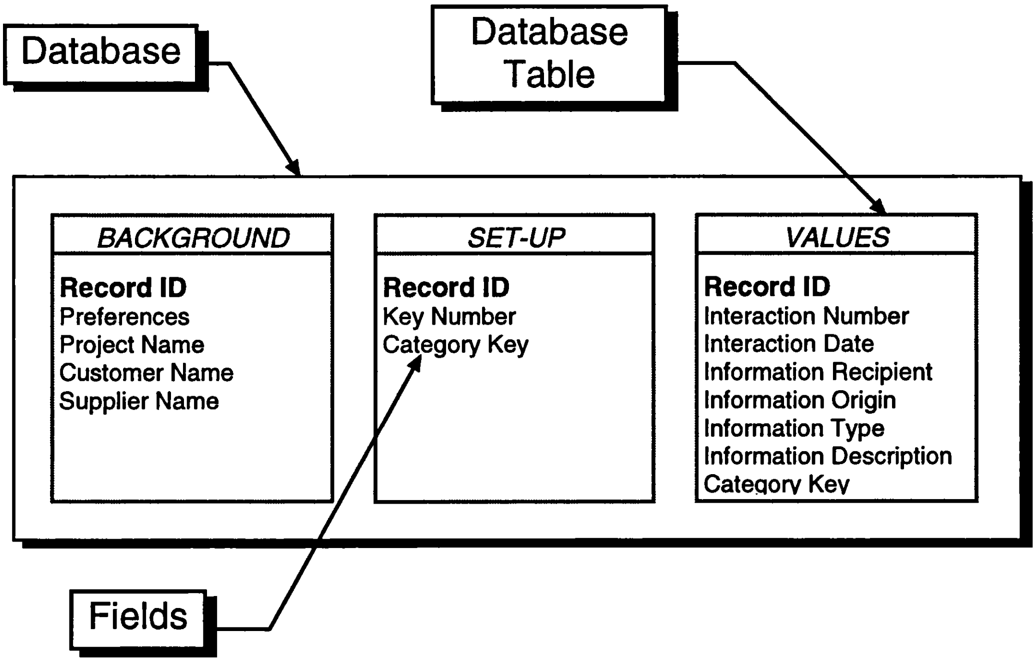

Figure 5.1: PIMS Data Storage Structure

Further details pertaining to the above may be inferred from subsequent sections, that provide details of the graphical user interfaces within PIMS.

5.3 User Interfaces

PIMS user interfaces can be grouped into two main areas, namely the input and model interfaces. Their development was a key aspect in both the realisation of PIMS and its subsequent utilisation within industry (Turban, [1988]; Sprague and Carlson, [1982]). Indeed, Fox [1994] has implied that if systems of this nature are to be utilised by engineering designers then they must both enable and entice the unintrusive acquisition of information. Consequently, as perhaps may be evident from the following sections, significant time and effort was put into developing the user interfaces.

5.3.1 Generic Aspects

On designing the structure of the database (outlined above) a decision was made to develop PIMS using Microsoft® Visual Basic®. The main reasons for the adoption of this programming environment were based on the following:

- *A relatively shallow learning curve.*
- *Simplicity of model implementation.*
- *Microsoft® Windows® compatibility.*
- *Compatibility with the Jet® engine.*

PIMS user interfaces are made up of a number of windows that will be highlighted throughout the remainder of this chapter. The overall interface itself, however, is constructed using the Multiple Document Interface (MDI) format (Figure 5.2).

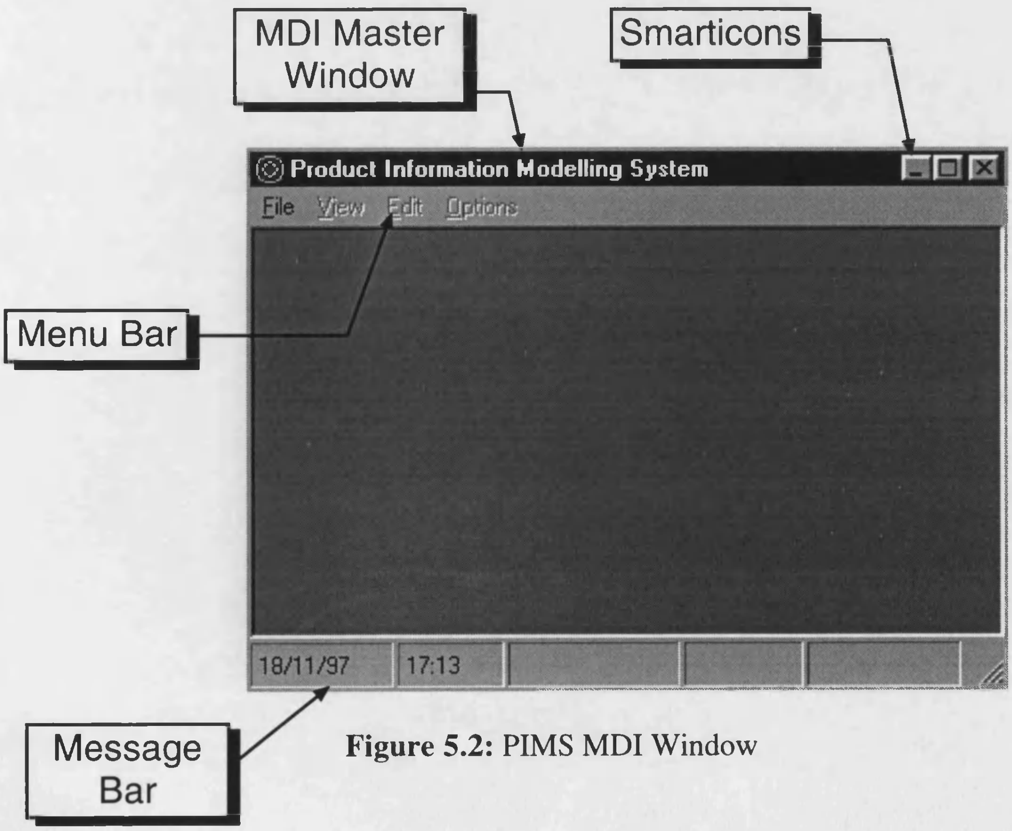

Figure 5.2: PIMS MDI Window

The MDI format, that is familiar to all Windows® users, allows several (child) windows to be displayed inside the master or MDI window. As shown in Figure 5.2, the MDI window contains the menus that control both it and each of the child windows' operations.

When the program is executed, a short time period elapses whilst the various database connections are made, the program variables initiated, and the MDI window displayed. On accessing the *File Menu* the user is faced with the choice of either exiting the program, opening an existing model, or creating a new model.

The following sections provide an overview of the procedures required to build a new model. Attention is placed upon the salient functions and features of PIMS.

5.3.2 PIMS Input Interface

All the data inputs for creating or updating a model can normally be performed from one window, namely the 'model building' window. The exception, however, is when *New Project* is selected from the *File Menu*. In this instance the user is required to enter a name under which the project is to be saved, and then input certain data into the 'database set-up' window, shown in Figure 5.3.

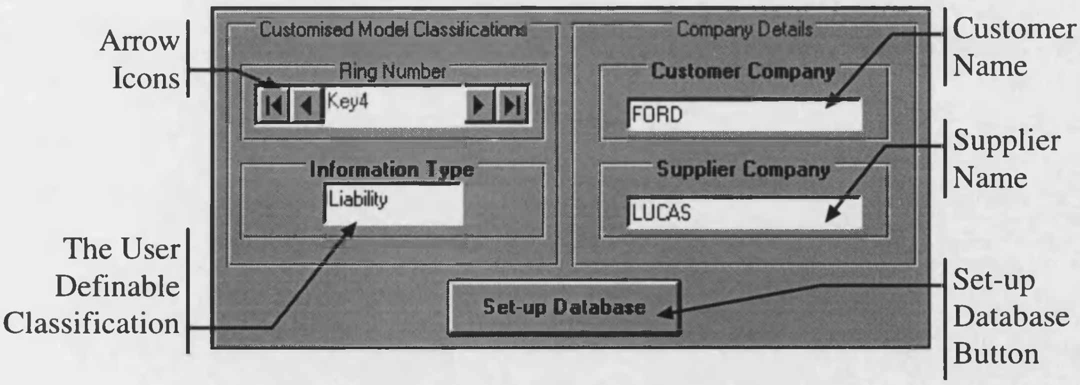

Figure 5.3: PIMS Database Set-up Window

The two main data types that must be entered into this window are outlined as follows:

1. The names of both the customer and the supplier involved in the design project. The user of PIMS may assume either of these roles, and by convention the customer is represented on the right had side of the model and the supplier on the left hand side.

2. A list of information categorisations[28] that are later used to classify information during the model building process. These are inputted via the keyboard and can be viewed by 'mouse clicking' the arrow icons shown in Figure 5.3. The order in which they are inputted affects the way that a model is displayed in the *Custom* display mode; 'Key 1' corresponds to the outer model ring and 'Key n' to the inner model ring. This will be further explained in due course.

When the *Set-up Database* button is clicked (Figure 5.3), the values inputted within this window are stored (for later use) in the 'Background' and 'Set-up' tables within the new project's database. Thereafter, the 'model building' window shown in Figure 5.4 is displayed; this may also be accessed by selecting *Update Model* from the *Edit* menu on the main MDI window.

The 'model building' window is effectively the front-end to a Microsoft® Access® database. By clicking the appropriate button within this window, the user can add new records or modify or delete existing records. Hence, the user can input all the necessary data to build or update a model. The seven main data or record types that the user is required to enter within this window (Figure 5.4) are outlined as follows:

1. Date of Interaction - the process of inputting a date when an information interaction took place has been automated by a 'drop down' calendar.

[28] Whilst undertaking the case design projects (Chapter 6) the main categorisations from the Meta classification were used (Appendix 1). These include, for example, *Form, Function, Fitness, Process, Time, Volumes, Liability, Handling*, and *Financial*.

➢ Data entry errors, time, and effort can be minimised by employing a 'multi-select' approach (Cumo *et al*, [1996]). This approach was widely adopted during the development of PIMS.

2. *Recipient* - the user is required to select either *Customer*, *Supplier*, or *3rd Party* from a 'drop down' list. This entry is used to indicate which party has received information during an interaction.

  ➢ The inclusion of *3rd Party* enables information interactions that are not connected to both the customer and the supplier to be incorporated within a model. Hence, this feature augments the modelling of customer-supplier information interactions in a 'network' sense rather than simply in a 'dyadic' sense.

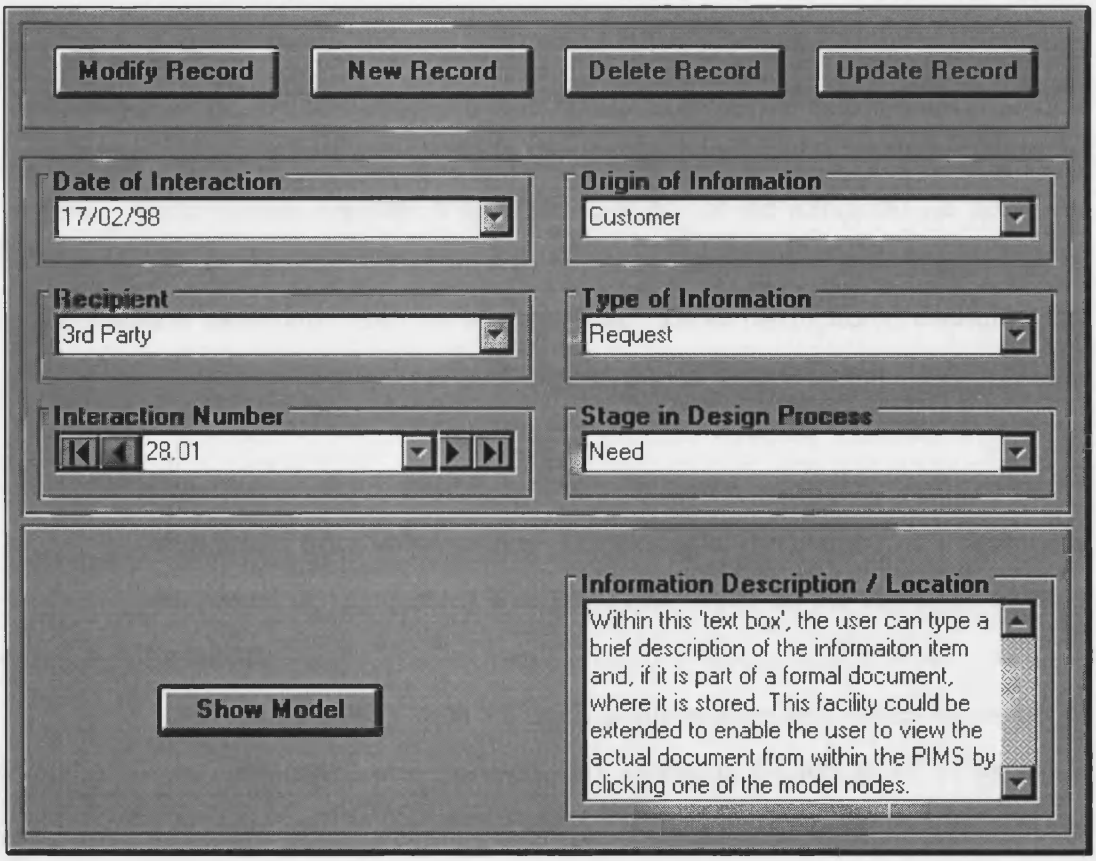

Figure 5.4: PIMS Model Building Window

3. *Interaction Number* - the user must assign a decimal number to each information interaction by selecting it from a 'drop down' list. The interaction number is used as the primary index for the records stored within the 'Values' table of a project's database.
   - The value before the decimal place corresponds to the numerical order in which an information interaction took place; the first interaction would be assigned the number 1.**, the second 2.**, etc.. The value after the decimal place corresponds to any item of information that may be associated with an interaction. For example, 1.01 corresponds to the first item of information (sent, received, accessed, etc.) in the first interaction (meeting, e-mail, fax, etc.) and 6.05 corresponds to the fifth item of information in the sixth interaction.

4. *Origin of Information* - the user must select either *Created, Extracted, Customer, Supplier*, or *3rd Party* from a 'drop down' list. In practice, however, the actual names of the organisations (stored in the 'Background' table) are presented to the user. These values, together with those selected for the *Recipient* (as described above), enable various distinctions to be made between the individual items of information associated with each interaction. These distinctions, assuming that *Customer* had been selected as the *Recipient*, are outlined follows:

   - *Extracted* - this would indicate that the customer had extracted information from some source. For example, the reading of a document. This would be represented as a *Light Blue Node* on the customer's half of the model.
     - The incorporation of such a distinction was believed to be an important consideration. For example, the receipt of a Fax would not (as implied in Section 4.2.3) necessarily mean that information had been imparted within the customer.

- *Created* - this would indicate that new information had been created by the customer. For example, the production of an engineering drawing. This would be represented as a *Green Node* on the customer's half of the model.

- *Customer* - this would indicate that information had been accessed from within the customer organisation. For example, the retrieval of a supplier catalogue from a global library. This would be represented as a *Dark Blue Node* on the customer's half of the model.
  - Again, the accessing of information by the customer does not necessarily imply that any information had been imparted within the customer.

- *Supplier* - this would indicate that the customer had received information from the supplier. For example, this may have been communicated via a Fax, a telephone conversation, a meeting, etc., or it may even have been the transfer of a physical object such as a 'widget' from the supplier to the customer. This would be represented as a *Red Node* on the customer's half of the model.

- *3rd Party* - this would indicate that the customer had received information from a *3rd Party*. As outlined above, this would be represented as a *Red Node* on the customer's half of the model.

Likewise, if *Supplier* had been selected as the *Recipient* of the information, the above conditions would apply in a similar manner. If however *3rd Party* had been selected as the *Recipient*, the user could then only select either *Customer* or *Supplier* from the *Origin of Information* list box. In such instances, this would be represented by a *Pink Node* on the customer's or the supplier's side of the model respectively. Hence, the sending of information to a 3rd party is represented rather than the receipt of information by a 3rd party.

5. *Type of Information* - the user must select one of the information categorisations from the list that was entered when the project was initially started (see Section 5.3.2). The selected entries are used to classify the individual items of information that are associated with each interaction.

6. *Stage in Design Process* - each item of information must be associated with one of the following stages in the engineering design process: *Need*, *Concept*, *Embodiment*, *Detail*, *Pre-fabrication*, or *Test*. The rationale behind this decision was outlined in Section 4.5.3, although it should be re-emphasised at this point that there is no reason why any other design process classification (or even any other classification) could not be used[29].

7. *Description of Information + Storage Location* - within this text box the user can type a brief description of the item of information and, perhaps more importantly, the user can indicate where it is stored. Hence, the database does not necessarily store all of the information associated with a design project. Rather, it indicates what that information is and from where it may be obtained. The text box is however particularly useful for capturing informal information interactions.

As outlined above, the data entry process has largely been automated and requires only a few mouse clicks to select data values. By clicking the *Update Record* button any data changes or additions are stored within the 'Values' table of a project's database. The text, combo, and data entry boxes are then disabled. At this stage the user can either continue to enter data or can display a model by clicking the *Show Model* button.

Details of the model interface and the key functions that can be performed within it are provide in the following section.

[29] This would only require minor modifications to the software code.

5.3.3 PIMS Model Interface

Within the 'model window' a model can be viewed by the user. An example model in its *Standard Activity Linear* display mode (to be described in due course) is shown in Figure 5.5.

Akin to the input interface (previously described) the words 'Customer' and 'Supplier' are represented within the 'model window' by the actual names of the customer and supplier. These values, that are stored within the 'Background' table of a project's database, indicate which side of a model corresponds to which party.

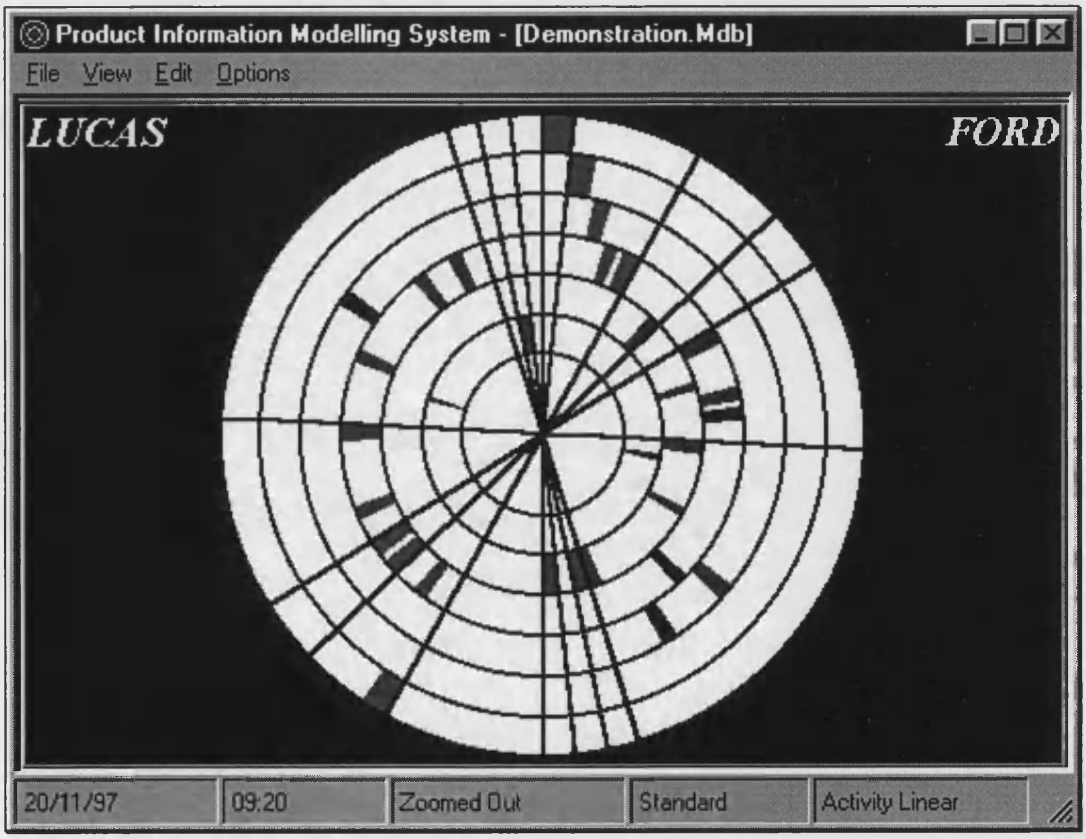

Figure 5.5: PIMS Model Window
(Standard Activity Linear Display Mode)

The main features and functions that can be performed within the 'model window' are outlined as follows:

1. *Model Key* - when activated, this dynamic label (Figure 5.6) indicates what the current ring under the mouse pointer represents. This avoids the need to add static labels to a model and hence minimises clutter.

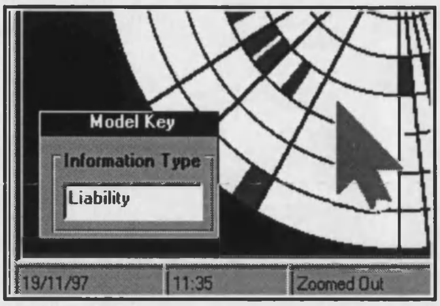

Figure 5.6: Model Key

2. *Description Window* - by clicking the left mouse button on any of the nodes in a model the window shown in Figure 5.7 pops up. This provides access to the description that was entered into the 'Description of Information + Storage Location' text box within the 'model building' window, described above.

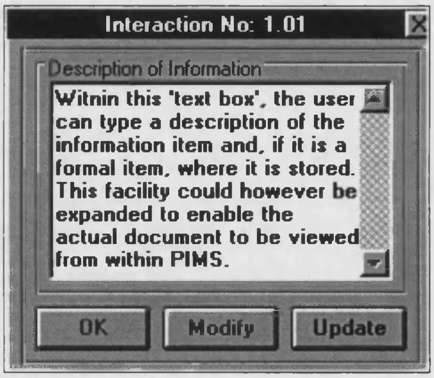

Figure 5.7: Description Window

3. *Date Window* - when the right mouse button is clicked on one of a model's nodes, the window shown in Figure 5.8 window pops up. This displays the date on which the corresponding information interaction took place.

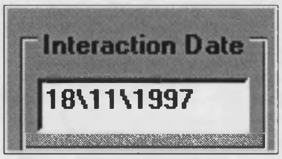

Figure 5.8: Date Window

4. *Zoom Model* - to simplify complex models, the area between two nodes on a model may be expanded to fill the whole model. These two nodes are selected by clicking them with the mouse. The 'Interaction Number' for each of these two nodes is displayed in the window shown in Figure 5.9.

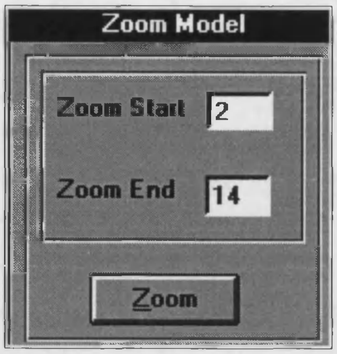

Figure 5.9: Zoom Model

5. *Project Statistics* - when activated, this window (Figure 5.10) provides details such as company names, design project start and end dates, total number of interactions, and total number of information items. In future releases of PIMS, however, this function could be expanded to provide additional information of interest, such as total time spent interacting.

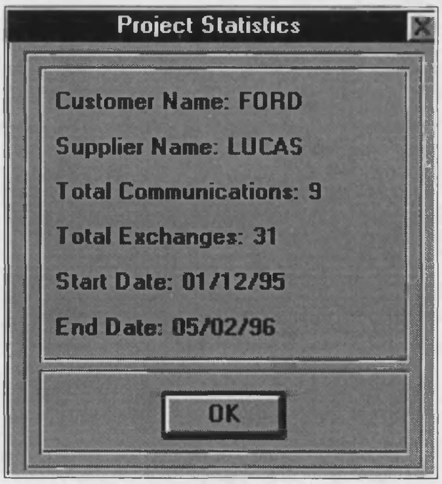

Figure 5.10: Project Statistics

6. *Standard / Custom Display Mode* - in the *Standard* display mode, each of the model rings represent stages in the design process (Section 4.5.3). In the *Custom* display mode, however, the model rings represent the user defined information categorisations that were entered when the project was initially started (Section 5.3.2). An example of a model in the *Custom* display mode (with 9 rings) is shown in Figure 5.11.

- This function therefore allows a model to be displayed from two entirely different viewpoints: the *Standard* one, emphasising phases in the design process, and the *Custom* one, which types of information are utilised or exchanged during the design process.

7. *Activity Linear / Time Linear Display Mode* - a model can be displayed in either an *Activity Linear* (as in Figure 5.11) or a *Time Linear Display Mode*. In the latter case, as outlined in Section 4.5.6, the degree of clockwise rotation is directly proportional to time.

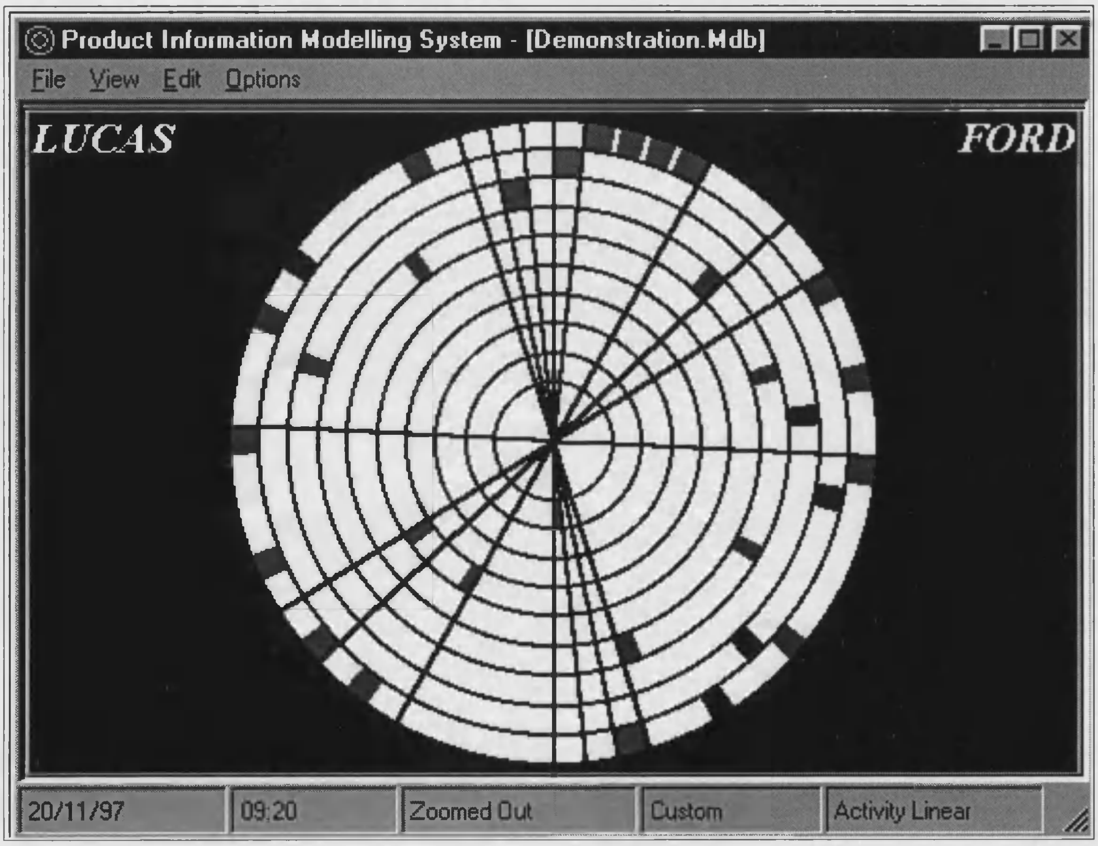

Figure 5.11: PIMS Model Window
(Custom Activity Linear Display Mode)

Within the 'model window' the user has access to the menus within the main MDI window, and can thus close, open, or create a new model, or go back to the 'model building' window to make changes or updates to a model.

5.4 Discussion of PIMS

As previously noted, PIMS was designed such that it could be utilised by engineering designers on a 'day to day' basis in order to aid the data collection process. Of further significance, however, it was designed in order to extend the capabilities of the MIM technique. An evaluation of PIMS in line with the five criteria, specific to this research, that were laid down in Section 4.4.1, is thus provided as follows:

1. *Represent the utilisation and the exchange of information*
   - The actions of *Creating*, *Extracting*, *Accessing*, or *Exchanging* information may be both represented and differentiated (by different node colours) within PIMS.
   - These actions may be further differentiated according to which party has carried them out and whether or not they involve both the customer and the supplier.

2. *Represent the quantities of information utilised and exchanged*
   - Information interactions are bounded by pairs of lines (start and end) and thus they may be represented quantitatively within PIMS. This value may be calculated by the *Statistics* function.
   - Each information interaction may be broken down in order to represent key items of information that are represented by nodes within PIMS. Exact quantities of information are not, however, represented.

3. *Represent interactions in the context of the design process*
   - In the *Standard* display mode models are centred around the engineering design process. The radial position of the nodes relates their corresponding information items to phases in the engineering design process.

4. *Represent the sequence or timing of information interactions*
   - In the *Activity Linear* display mode information interactions are represented in chronological order.

> ➢ In the *Time Linear* display mode information interactions are organised in chronological order such that their degree of clockwise rotation is proportional to the time at which they took place.

5. *Represent the impact of information on the engineering design process*
   - ➢ In reality it may not be possible to know for certain what information has influenced a particular event. However, owing to the quantitative manner in which information is represented within PIMS, it is considered that it may be possible to infer which items of information led to particular events, such as design process iterations. It is considered that the ability to make such inferences may be aided by displaying models in the *Custom* display mode.

It is thus clear that PIMS is able to meet the five modelling criteria. More generally, the realisation of PIMS has resulted in a computer-based modelling system that produces easy to read graphical models of a consistent notation; desirable characteristics that were highlighted in Section 4.5.1. Its full potential, however, although difficult to convey owing to the paper based nature of this thesis, should become more apparent in Chapter 6, that deals with its application in industrial contexts.

5.5 Summary

This chapter has presented the development of a new research vehicle termed the Product Information Modelling System (PIMS); a software package that was realised via the integration of the MIM technique (Section 4.5) with various classification schema. PIMS was shown to be a dynamic modelling system; it may be used in 'real time' to build and automatically update information interaction models of a design project as it progress.

An overview of the key functions and features of PIMS has been provided, together with a step-by-step guide to the model building process. This was shown to require a minimal number of mouse clicks to build a consistent model of information interactions in product development processes. PIMS was evaluated against the five modelling criteria and was shown to meet them. Its implementation and subsequent utilisation within industrial contexts was however seen to be a key aspect in both its evaluation and the attainment of the research hypotheses. Details of this are provided in the following chapter, Chapter 6.

Chapter 6.
Validation of PIMS

This chapter is primarily concerned with the application and validation of PIMS in a variety of industrial contexts. It provides an overview of four case design projects and presents key observations that resulted from their analysis using PIMS.

More specifically, this chapter outlines the research methodology and highlights the considerations that were made prior to and during the case design projects. It describes one case design project (A) in full, presents PIMS models that resulted from undertaking it, gives a summary of a further three case design projects (B to D), and presents and discusses a number of key observations and research findings.

Owing to the wide variability of engineering design, it was believed that the reader would gain only limited value from observations made on a 'case by case' basis. Hence, attempts were made to present only those observations of a (more) generic nature, that were evident from a number of the case studies. These have been supported by examples from the case design projects, and in particular case design project A and its associated PIMS models. This, as previously noted, was described in more detail than the other case design projects. Further details pertaining to these are however provided in Appendix 2.

6.1 Research Methodology and Considerations

PIMS was developed in such a way as to enable it to be used by engineering designers on a 'day to day' basis, in 'real-time' or almost 'real-time', to collect and simultaneously model case study data. In order to help ensure that it would be used, and that the data entered would be of sufficient quality, due consideration was given to both the design of its user interfaces (Section 5.3) and the way that it was applied within industrial contexts. An overview of the key considerations that were made prior to and during its application are provided in the sections that follow.

6.1.1 The Selection of Organisations

The identification of potential industrial collaborators was influenced by factors such as industry sector, supply chain position, company size, and previous company co-operation. Owing to time and resource constraints, however, company location also had a considerable bearing on the identification of collaborators; it was anticipated that a significant number of visits would be required in order to:

- Install the PIMS software on the companies' computers.
- Train the engineering designers in the use of PIMS.
- Sort out any software 'bugs' or utilisation difficulties.
- Provide general support throughout the case studies.
- Validate the case studies and gather any additional data.

In all, PIMS was utilised within three separate engineering organisations. Owing to the proprietary nature of the data collected, however, their identity has been concealed.

6.1.2 The Selection of Engineering Designers

As time constraints restricted the number of case studies that could be undertaken, cross-correlations were largely ruled-out. Hence, the engineering designers' qualifications, experience, age, etc., had little impact upon their selection. However, factors such as their attitude, dependability, thoroughness, and technology competence were, for obvious reasons, taken into consideration. Moreover, owing to the nature of this research, it was apparent that a good relationship with those engineering designers involved was a significant factor in terms of ensuring co-operation and success.

A close friend of the author, who fulfilled the above requirements, was working as an engineering designer within one of the collaborating companies. The selection of whom, for one of the case studies, negated the investment of extra time that would have been required to build a good relationship.

6.1.3 The Selection of Case Design Projects

Many factors were taken into consideration when selecting what were to become the case design projects. The more significant of these are outlined as follows:

- *Time scales* - time constraints restricted the selection of design projects to those with relatively short anticipated durations (less than three months). Moreover, by selecting such projects it was believed that:
  - Any feedback related changes could be implemented before this research work was concluded.
  - A more consistent level of motivation could be maintained within those engineering designers involved.

- *Design type* - from the three key types of design activity that were outlined in Section 2.3.3, namely, original, adaptive and variant, a variant design project was selected for the initial 'beta' testing. This decision was made to help ensure that the engineering designer could, during the analysis of the modelled case design project, answer questions regarding the rationale behind particular actions. The above range of design types was however covered by subsequent case studies.
  - The importance of this is emphasised by Ebert *et al* [1986], who reported that these different design activities "*...feature diverse uncertainties and accordingly require dissimilar information processing capabilities and different kinds of information flows for project success*".

6.1.4 The Implementation of PIMS

Having made the considerations outlined above and discussed them with the Technical Directors at each company, confidentiality agreements were entered into, the various case design projects were selected, and the PIMS software was installed on a number of computers within each of the design departments.

In order to raise awareness of and interest in the intended programme of research, a demonstration of PIMS was given to a selection of engineering designers from different groups within the various design departments. The engineering designers directly involved in the case studies were however given additional training in the use of PIMS and provided with a help manual. After a 2 week period, to enable them to become aquatinted with PIMS, they were re-visited in order to clarify any points and to provide them with further information regarding the data entry requirements for PIMS. Details of this are provided in the following section.

6.1.5 Intended Levels of Data Input

The engineering designers were required to input a complete 'set' of data pertaining to a particular information interaction into PIMS, as outlined in Section 5.3.2. In order to ensure a consistent level of granularity in model building, however, it was necessary to define, and relay to those involved, a number of the terms used in PIMS. Details of this are provided as follows:

- *Information interaction* - this was defined as including *all* formal communications, such as faxes and letters, along with *all* informal communications, such as telephone conversations and meetings. Each discrete 'event' was classified as one interaction. Furthermore, for the purpose of completeness, both the creation and extraction of key information, together with information accesses involving only one party, were also defined as interactions.

- *Information item* - an 'item' of information implies some kind of measure of information and, as noted in Section 1.4, this is very difficult to quantify. It was thus suggested that each information interaction should be broken down into the 'flow' of key or important items of information that could be discretely associated with the 'user definable' information classification (detailed below). Hence, any number of information items (limited by the software to a maximum value of 99) could be associated with each information interaction.

- *Information classification* - in order to both allow comparisons to be drawn between different case studies and to enable maximum gains to be made from the models, the Meta classification (Appendix 1) was entered as the 'user definable' classification when setting up each project (see Section 5.3.2). As outlined above, this was then used to classify each item of information. In addition, however, two further categories were added to the Meta classification, namely *Request* and *Various*. The inclusion of these was found, during 'alpha' testing, to lend enhanced understanding and to simplify the model building process.

As the case design projects were to be documented from the view points of the engineering designers, the above levels of granularity were not expected to be attained in respect of the involved suppliers or 3rd parties.

Details of case design project A are provided in the following section, Section 6.2, and an over view of case design projects B to D is provided in Section 6.3.

6.2 Case Design Project A

Case design project A was studied from the initial need through to the final manufacture. The study focused around the interactions and information flows that took place both within a 2nd tier company and between its interfacing companies, and in particular a 3rd tier (supplier) company (Figure 6.1). This will be further explained in the following sections. These provide a background to the (collaborating) 2nd tier company; a description of case design project A; and a summary of the data inputted into PIMS. The resultant models are displayed and discussed in later sections of this chapter.

6.2.1 Company Overview

The collaborating company was a medium sized engineering concern (turnover ~ £20 million, total employees ~ 300, engineering designers ~ 25) that produced largely metal to rubber bonded components for the automotive industry. In recent years, owing to supply base reduction trends, its position in the supply chain had tended to shift from 1st to 2nd tier. As a consequence, it had to interface with an OEM, a 1st tier company, and a number of 3rd tier companies. For example, the collaborating (2nd tier) company was responsible for the manufacture of rubber components, assembly work, and the vast majority of the product and tooling design work. The manufacture of metal components, tools, and test jigs, however, was out-sourced to 3rd tier companies.

6.2.2 Project Overview

The case design project undertaken, was for the *design and manufacture of a test jig* that was required to simulate a link arm in which a suspension bush was to be housed. The suspension bush, that had been designed and prototyped at the 2nd tier company, was just about to go into full scale production. The need for the test jig arose as the result of a late addition to the suspension bush specification. This addition, that in effect specified a *minimum* force necessary to push the suspension bush out of the link arm it was to be fitted in, was made by the OEM 2 years after the original specification had been drawn up.

This particular case design project involved the following key parties:

- *The OEM* - responsible for the complete vehicle.
- *The 1st tier company* - responsible for the vehicle suspension system.
- *The 2nd tier company* - responsible for the vehicle suspension bushes (*the* customer {collaborating company}).
- *The 3rd tier company* - responsible for the manufacture of the vehicle suspension bush test jig (*the* supplier).
- *The 4th tier company* - responsible for producing the test jig raw material.
- *The virtual suppliers* - responsible for the provision of information.

The relationships between these companies are represented in Figure 6.1.

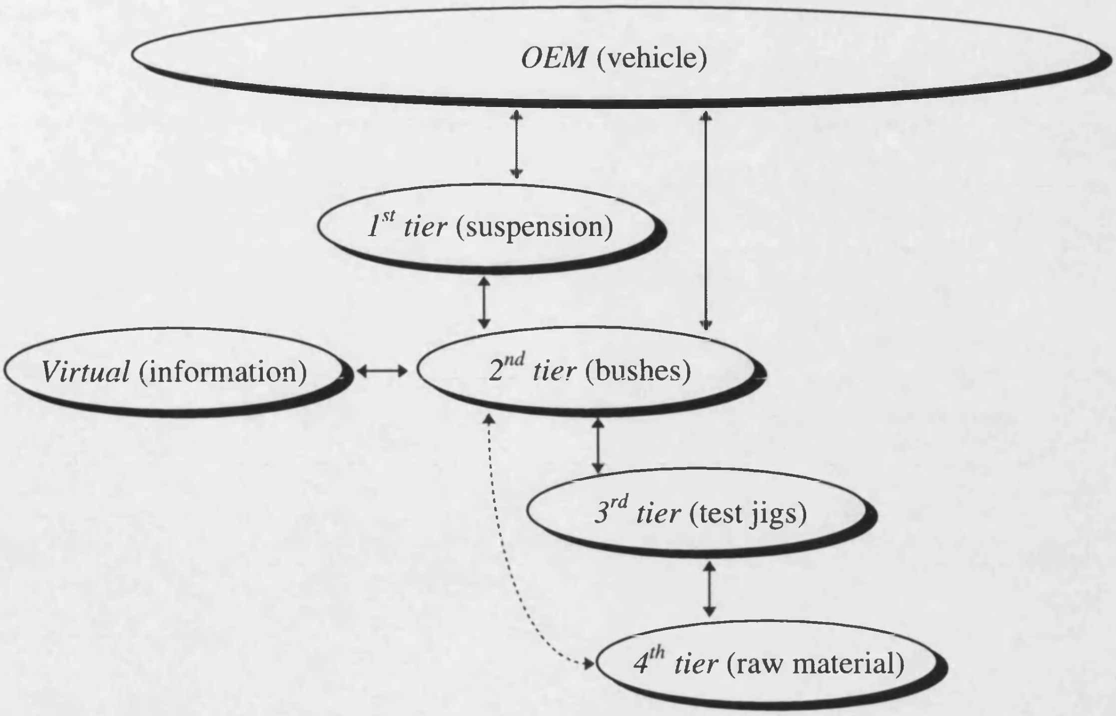

Figure 6.1: Company Relationships in Case Design Project A

6.2.3 Case Study Details

An overview of the activities that took place in case design project A is provided below. This is done in a chronological order in a narrative style to give the reader a feel for the events that took place in a busy design office. It is written from the perspective of the 2nd tier company, in which PIMS was utilised.

A DXF file containing the detail drawings of the suspension bush was sent by post from the 2nd tier company to the OEM for final approval on the 23/4/1997. A hard-copy of the approved detail drawings that had an additional border produced by the OEM was mailed back to the 2nd tier company on the 8/5/1997.

Subsequently, on analysing the detail drawings, the engineering designer at the 2nd tier company noted a requirement, within the OEM's drawing border, that had not appeared on the original suspension bush specification. This requirement specified that the bush had to be capable of withstanding a *minimum* lateral force without being pushed out of the link arm in which it was to be housed.

The engineering designer perceived that the bush would meet this additional requirement, but in order to verify this he decided that a number of experiments were necessary. In order to carry these out, however, a test jig that simulated the link arm (or part of it) was required, and hence the detail drawings of the interfacing link arm were also required. A hard-copy of these, dated 14/1/96, had been posted to the engineering designer on the 30/5/96 in order to enable the development of the suspension bush. The engineering designer therefore accessed the detail drawings from a local store.

The engineering designer proceeded to design the test jig, and throughout used information from both the detail drawings of the link arm and the detail drawings of the suspension bush. In the latter case, these were accessed directly from the CAD system.

On completing the detail drawings of the test jig, the engineering designer noted that the link arm material was only specified according to a Corporate and not a Corporate and a British Standard. As the test jig was to be manufactured in the UK, however, the material's equivalent British Standard number was required.

Subsequently, the engineering designer obtained a copy of the Corporate Standard for the material from a CD ROM that had been provided by the OEM. He then proceeded to search the British Standard for general engineering sections, maintained within the quality department, in order to find a material with the same or similar chemical and mechanical properties. The engineering designer, however, was unable to find an exact or even a similar equivalent. In fact, it became apparent that the material he was trying to match had a high silicon content and this made him more determined to track the equivalent British Standard; he was of the mind that the high silicon content may have had a marked impact upon the suspension bush push-out force.

The engineering designer decided that he needed more information on the link arm, and so on the end of a fax that he sent to the 1st tier (European) company, on the 22/5/1997, he requested detail drawings of the link arm that had, in fact, been designed by them. This request was based on the engineering designer's belief that the requested link arm drawings may have contained more information and been more current than those that had originated from the OEM, dated 14/1/96.

In addition, the engineering designer sent a fax to the 1st tier company on the following day, the 23/5/97, requesting the equivalent British Standard for the link arm material and the availability of reject link arms with the bush housings intact, such that, if available, they could then be used instead of the test jig.

On the 26/5/97, a fax was received from the 1st tier company confirming that the detail drawings of the link arm had been dispatched that day. The fax also indicated that there were no available reject link arms, although the 1st tier company suggested that a small batch could be manufactured at a specified unit cost. With regards to the equivalent British Standard, the 1st tier company confirmed that this was unknown, but details were provided of the equivalent American Standard. The engineering designer, on receiving the fax, decided that it would be too expensive to purchase new link arms for the purpose of testing, and hence decided to continue with the original idea of the test jig.

On the 29/5/1997, the engineering designer received a copy of the detail drawings of the link arm, dated 21/4/1997, through the post. On comparing them to those that he had received from the OEM, it was apparent that the material specification was the same. However, the engineering designer noted a number of dimensional variations which, if undetected, would have had a marked impact upon the push-out force. He therefore made dimensional changes to the detail drawings of the test jig, and continued his search for the material standard information.

The engineering designer was aware that one of his colleagues had recently been to a sister company in the USA, and so he asked him for details of a contact person who might be able to provide a copy of the British Standard for the material. Contact details were obtained, and subsequently, on the 5/6/1997, the engineering designer faxed details of the American and the Corporate material Standard, and requested the equivalent British Standard.

The following day, on the 6/6/1997, the engineering designer received a fax from the sister company. This included the material specification to the American Standard, but details of the British Standard were not given. The engineering designer, however, noted that the contact from the sister company had written 'steel castings' on the fax. He was slightly perturbed by this as he knew that the link arm was aluminium, but the word 'castings' triggered the engineering designer to realise that he may have looked at the wrong British Standard.

A few days later, on the 13/6/97, the engineering designer went back to the quality department and obtained a copy of the British Standard for casting materials. Analysis of this revealed a grade of aluminium that had 5 out of 10 chemical properties matched to those desired. The engineering designer was confident that the British Standard material was appropriate. In order to verify this, however, he sent a fax to the 1st tier company, on the 13/6/1997, detailing both the British and the Corporate material specifications and asked if the British Standard grade material would be acceptable for test purposes.

On the 16/6/1997, the 1st tier company sent a fax to the engineering designer confirming that the selected British Standard grade material was acceptable, as it had the same Mg and Si content. The engineering designer subsequently modified the detail drawings of the test jig by replacing the Corporate Standard for the material with the British Standard.

On the 17/6/1997, the engineering designer telephoned a 3rd tier company, that often undertook the manufacture of test jigs, and asked how much work they had on and if they could fit a job in. On confirming that this was possible, the engineering designer pre-warned the contact at the 3rd tier company that the test jig required a fancy aluminium, and told him that he would fax a copy of the detail drawings. The same day, on the 17/6/1997, the engineering designer faxed a copy of the test jig detail drawings to the 3rd tier company and requested details of manufacturing costs and delivery dates.

A few days later, on the 23/6/1997, the engineering designer, as he hadn't heard from the 3rd tier company, telephoned them to find out how the job was progressing. The engineering designer was informed that problems obtaining the specified material were being encountered. He made it clear, however, that regardless of cost it had to be obtained.

On the 25/6/1997, the 3rd tier company faxed details of the test jig manufacturing costs, together with the anticipated delivery date.

On the 26/6/1997, the engineering designer sent a fax to the 3rd tier company confirming the order for the test jigs, according to specified volume, price, and delivery requirements.

On the 10/7/1997, the test jigs were delivered to the 2nd tier company and no further communications took place between the engineering designer and the 3rd tier company with regards to them.

6.2.4 Summary of PIMS Models and Data

A summary of the data entered into PIMS by the engineering designer involved in case design project A is provided in Table 6.1. In this case the *customer* was the 2nd tier company and the *supplier* the 3rd tier company. The resultant PIMS models are shown and discussed in Section 6.5.

No.	Date	Recipient	Origin	Stage	Type	Summary
1.01	23/04/97	OEM	Customer	Need	Request	Drawings Approval
1.02	23/04/97	OEM	Customer	Need	Form	Bush Drawings
2.01	08/05/97	Customer	OEM	Need	Various	Approved Bush Drawings
2.02	08/05/97	Customer	Extracted	Need	Fitness	Bush Drawings
3.01	12/05/97	Customer	Created	Concept	Form	Test Jig Drawings
4.01	12/05/97	Customer	Accessed	Embodiment	Form	Link Arm Drawings
4.02	12/05/97	Customer	Extracted	Embodiment	Form	Link Arm Drawings
5.01	12/05/97	Customer	Accessed	Embodiment	Form	Bush Drawings
5.02	12/05/97	Customer	Extracted	Embodiment	Form	Bush Drawings
6.01	12/05/97	Customer	Created	Embodiment	Form	Test Jig Drawings
6.02	12/05/97	Customer	Created	Detail	Form	Material Standards
7.01	13/05/97	Customer	Accessed	Detail	Various	Material Standards
7.02	13/05/97	Customer	Extracted	Detail	Form	Material Standards
8.01	13/05/97	Customer	Accessed	Detail	Form	Material Standards
8.02	13/05/97	Customer	Extracted	Detail	Form	Material Standards
9.01	22/05/97	1st tier	Customer	Detail	Request	Link Arm Drawings
10.01	23/05/97	1st tier	Customer	Detail	Request	Material Standards
10.02	23/05/97	1st tier	Customer	Concept	Request	Link Arm
11.01	26/05/97	Customer	1st tier	Detail	Various	Material Standards
11.02	26/05/97	Customer	1st tier	Concept	Various	Link arm
11.03	26/05/97	Customer	Extracted	Concept	Various	Link Arm
11.04	26/05/97	Customer	Extracted	Detail	Form	Material Standards
12.01	29/05/97	Customer	1st tier	Detail	Form	Link Arm Drawings
12.02	29/05/97	Customer	Extracted	Detail	Form	Link Arm Drawings
13.01	29/05/97	Customer	Accessed	Detail	Form	Link Arm Drawings
13.02	29/05/97	Customer	Extracted	Detail	Form	Link Arm Drawings
14.01	29/05/97	Customer	Accessed	Detail	Form	Test Jig Drawings
14.02	29/05/97	Customer	Created	Detail	Form	Test Jig Drawings
15.01	05/06/97	Colleague	Customer	Detail	Request	Contact Name
15.02	05/06/97	Customer	Colleague	Detail	Various	Contact Name
16.01	05/06/97	Customer	Accessed	Detail	Various	Material Standards
16.02	05/06/97	Customer	Extracted	Detail	Form	Material Standards
17.01	05/06/97	3rd Party	Customer	Detail	Request	Material Standards
17.02	05/06/97	3rd Party	Customer	Detail	Form	Material Standards
18.01	06/06/97	Customer	3rd Party	Detail	Various	Material Standards
18.02	06/06/97	Customer	Extracted	Detail	Form	Material Standards
19.01	13/06/97	Customer	Accessed	Detail	Form	Material Standards
19.02	13/06/97	Customer	Extracted	Detail	Form	Material Standards
20.01	13/06/97	1st tier	Customer	Detail	Request	Standards Approval
20.02	13/06/97	1st tier	Customer	Detail	Form	Material Standards
21.01	16/06/97	Customer	1st tier	Detail	Various	Approved Standards
21.02	16/06/97	Customer	Extracted	Detail	Fitness	Material Standard
22.01	16/06/97	Customer	Accessed	Detail	Form	Test Jig Drawings
22.02	16/06/97	Customer	Created	Detail	Form	Test Jig Drawings
23.01	17/06/97	3rd tier	Customer	Pre-fabrication	Request	Workload Details
23.02	17/06/97	Customer	3rd tier	Pre-fabrication	Time	Workload Details
23.03	17/06/97	3rd tier	Customer	Pre-fabrication	Form	Material Details
24.01	17/06/97	3rd tier	Customer	Pre-fabrication	Request	Best Quote
24.02	17/06/97	3rd tier	Customer	Pre-fabrication	Form	Test Jig Drawings
25.01	23/06/97	3rd tier	Customer	Pre-fabrication	Request	Progress Report
25.02	23/06/97	Customer	3rd tier	Pre-fabrication	Time	Progress Details
25.03	23/06/97	3rd tier	Customer	Pre-fabrication	Form	Material Details
26.01	25/06/97	Customer	3rd tier	Pre-fabrication	Various	Best Quote
26.02	25/06/97	Customer	Extracted	Pre-fabrication	Time	Best Quote
26.03	25/06/97	Customer	Extracted	Pre-fabrication	Financial	Best Quote
27.01	26/06/97	3rd tier	Customer	Pre-fabrication	Volumes	Production Confirmation
28.01	10/07/97	Customer	3rd tier	Pre-fabrication	Various	The Test Jigs

Table 6.1: Summary of Data Entered into PIMS

(Case Design Project A)

6.3 Case Design Projects B to D

This section provides a brief overview of a further 3 case design projects, that were studied from the initial need through to the final manufacture. In each case design project, the design work was undertaken within the customer company and the manufacture within the supplier company. For additional details on these case design projects, together with a selection of PIMS models, the reader should refer to Appendix 2.

6.3.1 Case Design Project B

This case design project was concerned with the design of a position adjustable knife edge that was required to eliminate a 'laser shadow' within a scanner. The need for the artefact arose whilst the scanner was being tested. The original design was modified during a meeting that took place between the engineering designer and the supplier immediately after the 'first off' knife edge had been manufactured. Further details are provided as follows:

- Design type - original
- Volumes - 25 per year
- Customer to supplier - 8 Km

6.3.2 Case Design Project C

As will be later explained (Section 6.6), a key reason for studying this particular case design project was that it was similar in nature to case design project A. It was concerned with the design of a fixture to enable the testing of a radiator anti-vibration mount. Immediately prior to manufacture the supplier suggested modifications to the original design that would improve its manufacturability. Further details are provided as follows:

- Design type - variant
- Volumes - one off batch of 10
- Customer to supplier - 16 Km

6.3.3 Case Design Project D

This case design project was concerned with the design of a metal bracket that formed part of a vehicle exhaust mount. Owing to high ultimate production volumes the engineering designer was particularly concerned with reducing manufacturing costs. Subsequent to the original detail drawings being produced, however, the supplier suggested a number of cost reducing design modifications. These changes were implemented before manufacture was commenced. Further details are provided as follows:

- Design type - adaptive
- Volumes - initial batch of 25
- Customer to supplier - 25 Km

6.4 PIMS Models

A selection of PIMS models that were produced as a result of case design project A are outlined in Table 6.2. These are presented and discussed in the following section, that outlines the key observations and findings that resulted from their analysis, together with the analysis of PIMS models for case design projects B to D, displayed in Appendix 2.

	Activity Linear	*Time Linear*
Standard	Figure 6.2	Figure 6.7
Custom	Figure 6.5	Figure 6.6

Table 6.2: Description of Case Study Models

To aid the interpretation of PIMS models presented within this chapter (and within Appendix 2) a number of 'keys' have been produced. These are provided in the following section.

6.4.1 Analysing PIMS Models

In order to decipher the meaning of the different node colours, represented within any PIMS model, the reader should refer to Table 6.3. Should further information be required on, for example, the display modes, the interaction types, or the modelling technique itself, the reader should refer to Chapters 5 and 4.

Interaction	Node Colour
Extracted	*Light Blue*
Received	*Red Node*
Accessed	*Dark Blue*
Created	*Green Node*
3rd Party	*Pink Node*

Table 6.3: Colour Key for the PIMS

When analysing PIMS models displayed in the *Standard* display mode, the reader should refer to Table 6.4 in order to obtain details of the information categories associated with each of the model rings.

Outer Ring → *Inner Ring*

Ring Number	1	2	3	4	5	6
Deign Phase	Need	Concept	Embodiment	Detail	Pre-fabrication	Test

Table 6.4: Model Key for the *Standard* Display Mode

Similarly, when analysing those models in the *Custom* display mode, the reader should refer to Table 6.5.

Outer Ring → *Inner Ring*

Ring No.	1	2	3	4	5	6	7	8	9	10	11
Category	Request	Various	Form	Function	Fitness	Process	Time	Volumes	Liability	Handling	Financial

Table 6.5 Model Key for the *Custom* Display Mode

6.5 Observations and Findings

A large number of observations were made in relation to the case design projects outlined in the previous sections. In general, these resulted from the following activities:

- Analysis of the data that was collected whilst the case design projects were being undertaken.
  - This included both the models produced by PIMS together with the data entered into PIMS.
  - This data also included formal documents, such as standards, faxes, and engineering drawings; that were 'used' within the case design projects.

- Interviews that were carried out with those parties involved in the case design projects.
  - Often these were undertaken in order to verify or expand upon the observations that emanated from the aforementioned analyses.
  - PIMS frequently formed a focal point for discussion and data elicitation during these interviews.

The following sections present and discuss the observations of a more generic nature. These will be supported by examples from the various case design projects, and case design project A in particular.

Owing to various constraints, that include, for example, the number of case studies that could be undertaken, the variability of the case studies, and the 'paper based' nature of this thesis[30], it was difficult to support each and every observation to the extent desired by the author. However, it is considered that these observations, in addition to their value *per se*, should serve to highlight both the applicability of PIMS and the potential gains that could be made by utilising it in real engineering design situations.

6.5.1 Information Acquisition Mechanisms

Having undertaken the aforementioned case studies, efforts were initially concentrated upon understanding how engineering designers acquired information from suppliers. Attention was therefore focused upon the information represented by the red nodes on the customers' halves of PIMS models, as shown in Figure 6.2 for example. Subsequently, it was possible to identify three distinct information acquisition mechanisms and hence three distinct types of acquired information. These have been defined as follows:

- I_r - random information, that enters the design process at random.
- I_{rq} - requested information, that is pulled into the design process.
- I_l - logical information, that is pushed into the design process.

By definition, it is not possible to influence the mechanism by which I_r is acquired, and it thus considered that it should not be relied upon as means of exploiting the information available from suppliers.

However, it is possible to influence the mechanisms by which I_{rq} and I_l are acquired. Hence, with a view to exploiting the information available from suppliers, these mechanisms will be discussed within the following sections. Their discussion is

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[30] When analysing models using the PIMS software it is possible to, for example, rapidly view further details about the interactions (including the dates when took place) by mouse clicking on the nodes; focus on particular interactions by utilising the zoom function; and to switch between different display modes when zoomed into a model. These functions were outlined in Chapter 5.

somewhat difficult, however, as not only are they inter-dependant but, as should become apparent, the acquisition of I_l is also dependant upon another category I_p, defined as follows:

➢ I_p - provided information, that is pushed out of the design process.

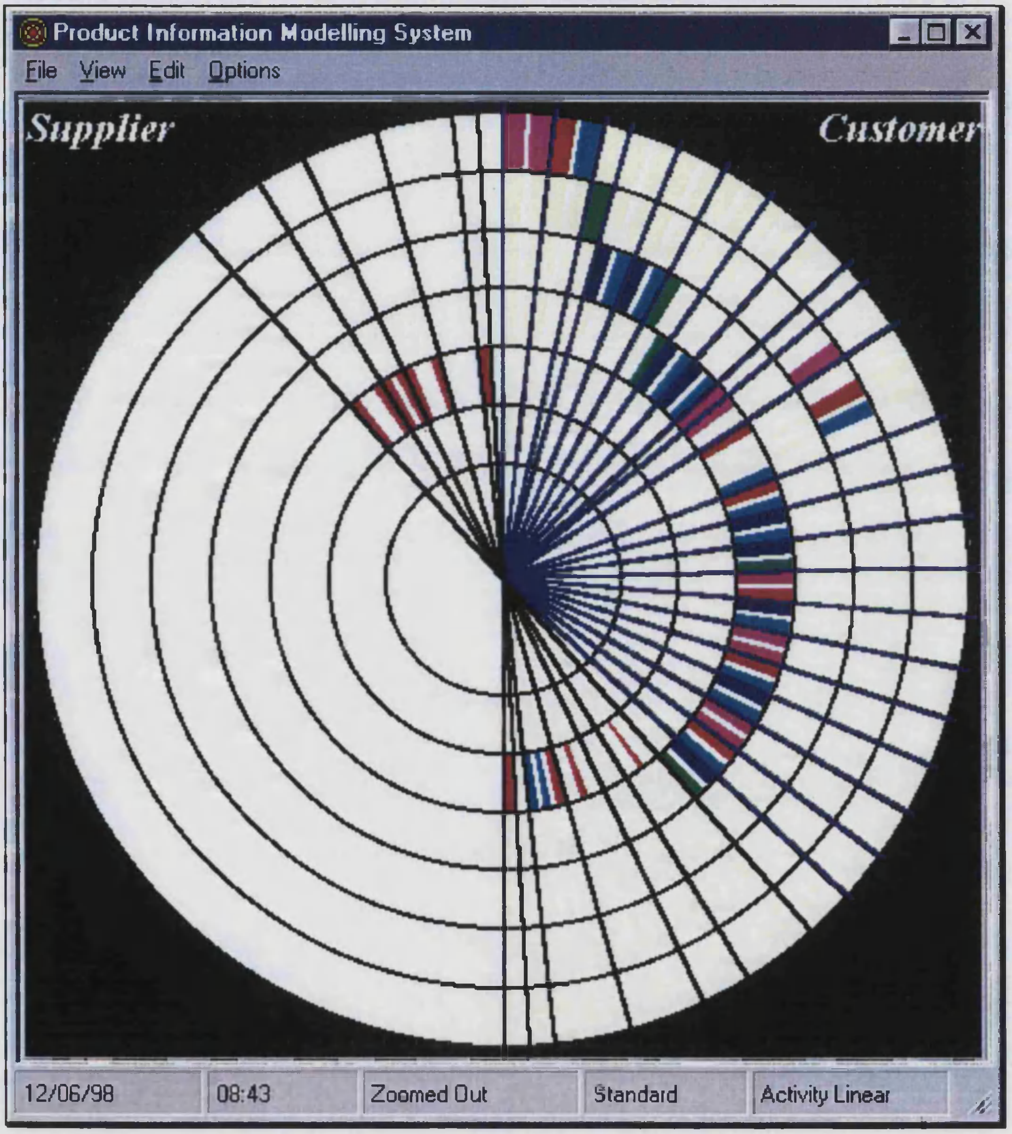

Figure 6.2: PIMS Model for Case Design Project A
(Standard Activity Linear Display Mode)

6.5.2 Requested Information (I_{rq})

When analysing the mechanism by which I_{rq} is acquired, it is apparent that some form of *decision* must precede the acquisition. Hence, in order to model or represent the processes involved in this decision, guidance was sought from the field of decision theory. Subsequently, it was revealed that the decision process (Figure 6.3) may be considered in terms of the following key stages: recognition, thought, judgement, and action.

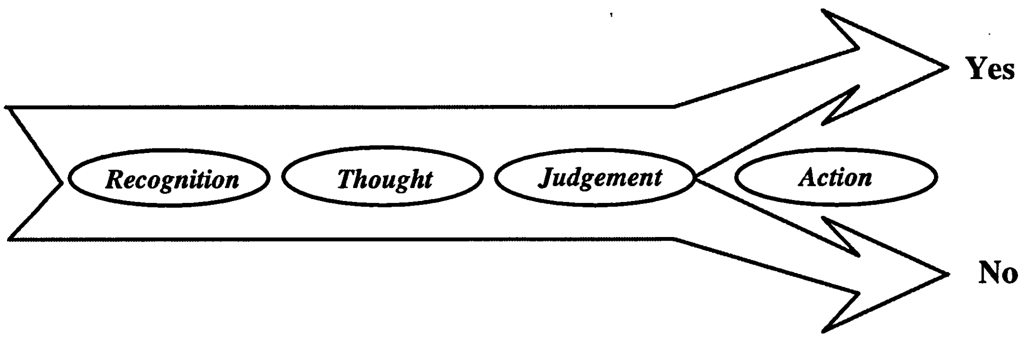

Figure 6.3: The Information Request Decision

The first stage in the decision process, namely *recognition* (Figure 6.3), is the most important; a point that is emphasised by Cornell [1980], who stated that "*if there is no decision-making situation there can be no decision, no alternatives*". Recognition, however, is a cognitive process that is dependant on, for example, the information stored within an engineering designer's mind, and hence it is open to 'human error'. It is considered, therefore, that if engineering designers rely solely upon I_{rq} the information available from suppliers may not always will be exploited to its full potential. For example:

- *Case design project B* - the design was not suited to the specified manufacturing process; during manufacture the artefact deflected and as a consequence it was not straight enough to fulfil its original needs.

➢ When questioned, it was revealed that the engineering designer had not recognised the need to request from the supplier (available[31]) information pertaining to the artefact's deflection during manufacture as he had not realised that the manufacturing process, specified by him, would cause the artefact to deflect in the first instance.

Following the *recognition* of the need for information the engineering designer must ultimately make a (Yes-No) decision on whether to request or not to request that information from the supplier (Figure 6.3). This decision, however, may be influenced by a multitude of factors over which control may be limited (Burns and Vicente, [1996]). For example, the time taken between request and receipt, the value of the information, or whether the information has previously been requested. More significantly, though, this decision may be influenced by whether or not engineering designers know or, more specifically, perceive they know this information already. For example:

- *Case design project A* - the engineering designer selected the 3rd tier company without requesting from them any information pertaining to their capabilities.
  ➢ When questioned, the engineering designer stated that he already knew this information because he had dealt with them in the past.

It is thus believed[32] that a correlation, such as the one shown in Figure 6.4, may exist between an engineering designer's perceived domain knowledge and the level of information requests made to suppliers, and in turn this may prove to be a source of problems. For example, it was noted in the above case that the 3rd tier company had no formal procedures in place for informing their customers of capability changes and, perhaps as a consequence, discrepancies between the engineering designer's

[31] Analysis of PIMS models for this case design project revealed that after the design failure had occurred this information was then provided by the supplier!

[32] Similarly, in the context of decision accuracy, Devine and Kozlowski [1995] found that high knowledge individuals had a reduced search for information.

perceived and actual knowledge were noted[33]. In this instance, however, these discrepancies did not affect the resultant artefact as the supplier's capabilities had increased and not reduced. Yet, this does serve to emphasise what could be a possible downfall of close relationships as it is thought more likely that the engineering designer would have requested this information in a more distant or new relationship.

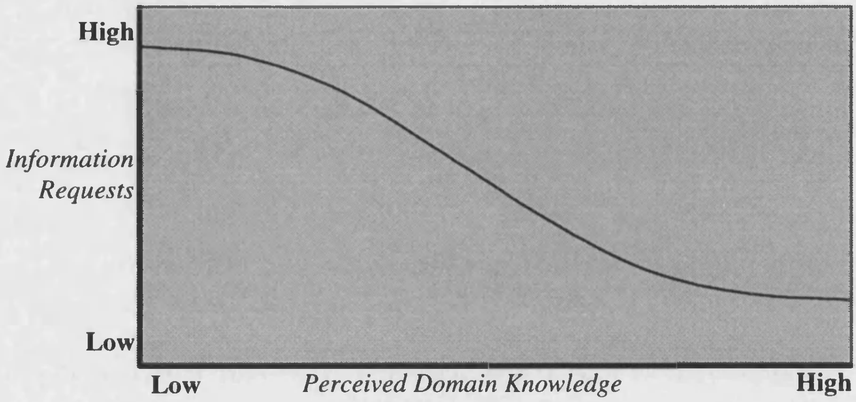

Figure 6.4: Supplier Interaction Versus Perceived Knowledge

Analysis of PIMS models, and in particular the nodes displayed in ring 1 (of, for example, Figure 6.5), revealed that the engineering designers involved in the case design projects seldom requested information that could have improved the quality of the resultant designs. This analysis also resulted in the identification of two types of request that were commonly made to suppliers. These, as outlined below, have been termed *closed* and *procedural* requests:

- *Closed requests* - requests for specific items of information.
  - For example, in case design project A the engineering designer faxed a contact in an American sister company with a request for a copy of the material specification for Aluminium ASTM - A 356 T6.

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[33] The 3rd tier company had recently acquired a new CNC milling machine; the engineering designer was not aware of this acquisition.

- *Procedural requests* - requests for what may be termed procedural information.
  - For example, in case design project A the engineering designer faxed the 3rd tier company with a request for the 'best quote and delivery' of the test jig.

It is considered that the above request types may not lend themselves particularly well to the acquisition of I_l; this will be discussed in later sections.

In summary, it should be clear that there is a need to address the issues surrounding the engineering designers' reliance upon memory, the nature of the information requests made to suppliers, and, more importantly, the engineering designers' sole reliance upon I_{rq}; that is if both design failures are to be avoided and the information available from suppliers is to be exploited to its full potential. These issues will be further discussed within subsequent sections.

6.5.3 Logical Information (I_l)

In a similar manner to the acquisition of I_{rq} a decision must precede the acquisition of I_l. In this instance, though, the decision, to effectively push information into the engineering design process, is made by the supplier. Yet prior to this decision the supplier must recognise the need to make it, and hence must be provided with information (I_p) pertaining to the design project in hand.

In contrast, by analysing the red nodes on the suppliers' halves of the PIMS models (e.g. Figure 6.5), it was revealed that the engineering designers seldom explicitly provided suppliers with information over and above that necessary for them to perform their tasks. However, information that resulted in the acquisition of I_l was, on a number of occasions, provided 'unintentionally' as a result of requests made to suppliers. For example:

- *Case design projects C and D* - after having received requests for 'best quote and delivery' information, the suppliers suggested a number of design modifications

(I_l); this information had not been requested by the engineering designers (further discussion of this is provided in Section 6.5.4).

Regardless of the engineering designers 'intentions', it is considered that the acquisition of I_l is heavily dependant upon both the timing of information provision and the communication media employed. This view is based on the fact that recognition is dependant upon the prevalence of information within the mind (Hirokawa and Poole, [1986]), and in-turn this is dependant upon when and how that information was last considered (Hauschildt, [1992]).

Further, it considered that the acquisition of I_l is also dependant upon the types of information that are provided to suppliers. Discussion of this will be presented within the following sections, that provide details of the information types involved, the communication media used, and the timing of the interactions within the case design projects.

6.5.4 Information Type

As noted in Section 6.1.5, the Meta classification (Appendix 1) was used as the 'user definable' classification when setting up each case design project; this was developed in order to represent the types of information that it was believed <u>should</u> be exchanged between customers and suppliers during multi-organisational product design and manufacture. By analysing PIMS models displayed in the *custom* display mode (e.g. Figure 6.5 and Figure 6.6) it was therefore possible to establish the extent to which these information types were created, accessed, extracted, shared, or received, during the case design projects.

It can seen from Figure 6.5 that a large proportion of the information interactions in case design project A related to the artefact's form (nodes in ring 3), whereas few related the artefact's function, fitness, process, liability, or handling (see Table 6.5). This was also found to be true of the other case design projects (e.g. those in Appendix 2). The implications of this are thought to be considerable, especially in the context of this present research, for example:

- *Case design project B* - prior to the previously noted design failure (Section 6.5.2) the supplier had not explicitly been provided with information pertaining to the artefact's function or how its function was to be assessed.
  - Subsequent to the design failure the supplier was explicitly provided with this information. The supplier proceeded to suggest modifications to both the design and its initial method of manufacture (I_l).

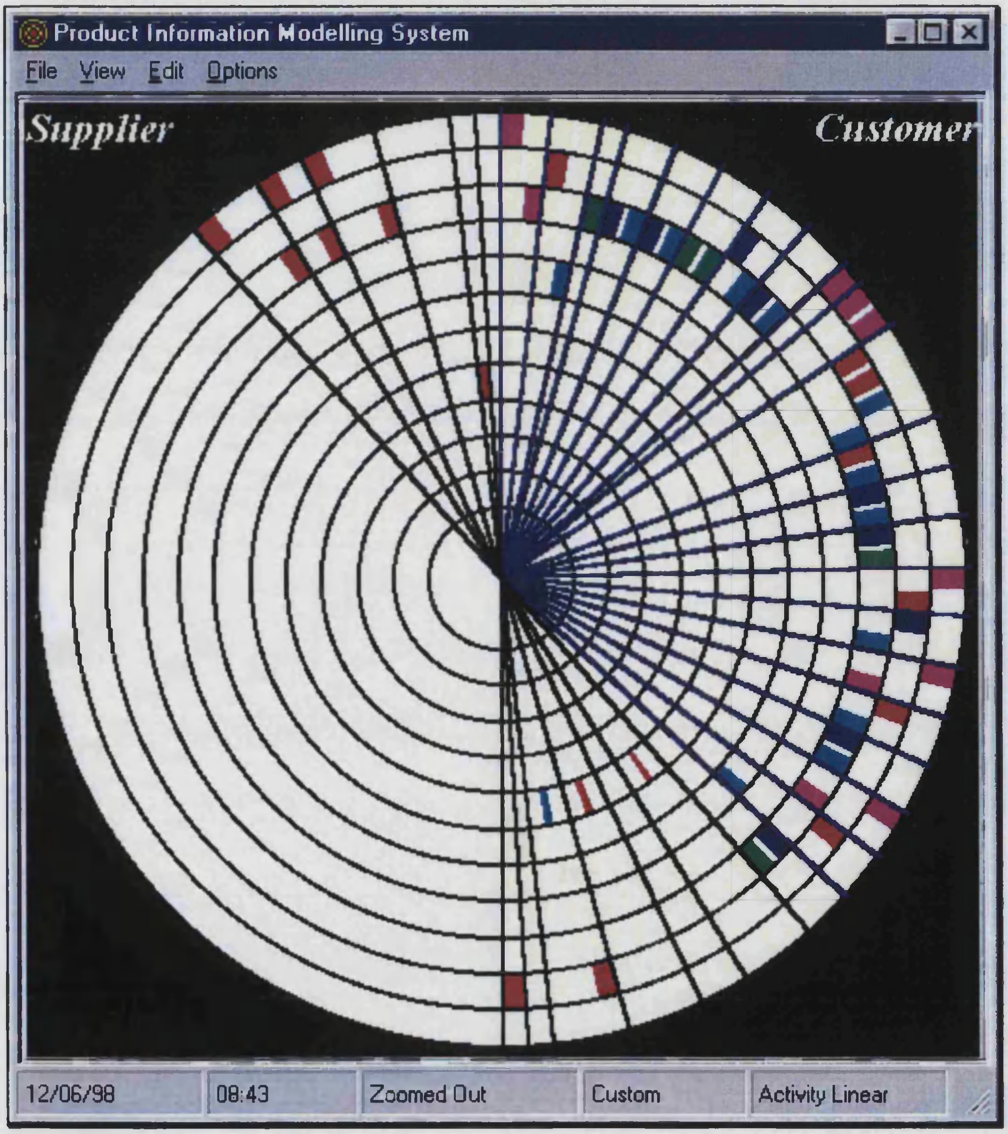

Figure 6.5: PIMS Model for Case Design Project A
(Custom Activity Linear Display Mode)

It is considered, as may be evident from the above, that the acquisition of I_l may be inhibited if the supplier is not provided with information (I_p) pertaining to an artefact's function or how its function is to be assessed. Or, more specifically, if the supplier cannot infer this information from that which has been provided; in the above example the supplier was unable to infer this information from the detail drawings, whereas in the following example the suppliers <u>were</u> able to make such inferences:

- *Case design projects C and D* - prior to manufacture the suppliers suggested design modifications (I_l) even though they had not explicitly been provided with information pertaining to the artefacts' function or fitness.
  - ➢ When interviewed it was revealed that the suppliers had inferred the functions of the designs from the detail drawings that they had received as a part of the requests for 'best quote and delivery' information.

The following example should also serve to emphasise one of the many implications of engineering designers not taking on board the wider issues of design, and especially at an appropriate phase or time in the engineering design process.

- *Case design project A* - during an interview with the engineering designer it was revealed that the need for the test jig (case design project A itself) could have been anticipated, prior to the late addition to the bush specification, if more attention had been placed upon the fitness of the bush itself.
  - ➢ In this instance no modifications to the bush design were required. According to the engineering designer, however, if modifications had been necessary then high costs would have been incurred, as the bush was just about to enter full scale production.

6.5.5 Interaction Timing

Firstly, it was noted that the information interactions in the case design projects occurred in bursts or clusters. This can be seen clearly from Figure 6.6 that shows a PIMS model for case design project A in a time linear mode (see Appendix 2 for further examples). Similar findings to this were reported by Hameri and Nihtila [1995] who studied engineering designers communicating over the world wide web. They attributed it to the fact that "*...work flows in discrete steps and the overall project process is the result of a turbulent communication phenomenon*".

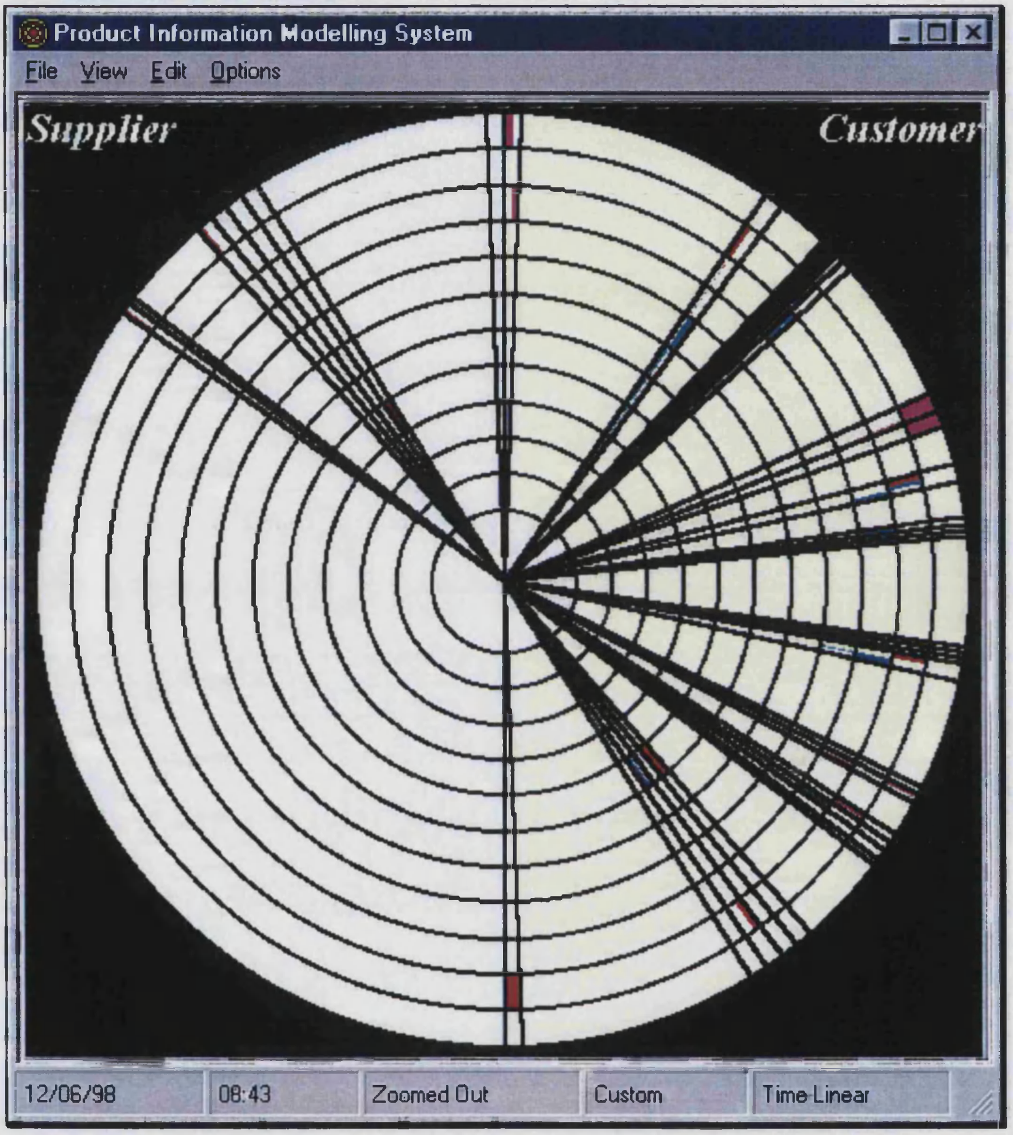

Figure 6.6: PIMS Model for Case Design Project A
(Custom Time Linear Display Mode)

Within this research, the turbulent activity was attributed to factors such as the engineering designers having to wait for requested information and their involvement in other design projects. The former was gauged from analysing PIMS models displayed in a custom time linear display mode, and in particular the time taken between information request and receipt (see for example Figure 6.6). The latter was gauged from Table 6.6 that shows, for a one month period in the middle of case design project A, a summary of all the additional external communications in which the engineering designer was involved[34]. From this it should be clear that the engineering designer's focus frequently switched between a number of design projects.

	Communication Media & Direction of Communications					
	Phone		Fax		Visit	
	Incoming	Outgoing	Incoming	Outgoing	Incoming	Outgoing
Communications with a supplier	3	18	1	7	0	3
Communications with a customer	13	29	3	11	0	2
Communications in total	*16*	*47*	*4*	*18*	*0*	*5*

Table 6.6: Communication Media and Direction Breakdown

Secondly, conflicts of opinion were noted in Section 2.3.2 as to whether or not a design is or should be progressed through the phases of the engineering design process in a linear manner. From PIMS models displayed in a standard display mode it was apparent that in practice both linear and non linear progression occurs, for example:

- *Case design project A* - with reference to Figure 6.2 it can be seen that up until and beyond the detail design phase, the phases were progressed through in a linear fashion (the concept information related to the use of reject link arms, that were not utilised).

[34] The engineering designer involved in case design project A was asked to record certain information, including that presented in Table 6.6, as a part of an additional research theme. This aimed to establish the existence of a correlation between types of communication media and the types of information exchanged; it has not been included within this thesis.

- *Case design projects B, C and D* - the phases were progressed linearly up until the detail design phase but, owing to design modifications, iterations took place between the pre-fabrication and detail phases (C and D) and the test and embodiment phases (B).

Thirdly, the aforementioned design process models (Section 2.3), that were primarily developed to aid engineering designers, tend only to represent the engineering design process up until the detail design phase. From PIMS models, however, it was apparent that a significant number of interactions took place after the detail design had been completed; this can clearly be seen from Figure 6.2 and PIMS models in Appendix 2. Hence, if the design process models are to serve their purpose more appropriately, or at least in instances where suppliers are involved, it is considered that they should be extended to take account of the phases beyond the detail design phase. Further, it is considered that they should also be extended, in general, to take into account interactions with external parties such as suppliers.

The extensions suggested above should not however detract from the importance placed upon the phases up until and including the detail design phase, and especially the preliminary phases in which overall product quality and cost are largely fixed (Section 2.3.2). This, however, is an area in which the engineering designers involved in the case design projects appeared to have paid little attention. For example, it can be seen from Figure 6.2 (and Figure 6.5) that no external information was requested or acquired by the engineering designers prior to the detail design phase, and that many of the information interactions were in fact related to this phase. This was largely found to be true of the other case design projects. It is thus apparent that a disproportionate amount of the engineering designers' time and effort may have been put into phases of the engineering design process in which only marginal improvements in cost and quality could have been made.

It was also clear from the graphical representation of PIMS models that in all the case design projects the engineering designers made no contact with the suppliers (responsible for manufacture) until a considerable amount of the overall product development time had elapsed. This can be seen from the large 'gap' in the bottom left hand corner of Figure 6.7 for example. Further, by the time the suppliers had been contacted the detail design work had in effect been completed. This however is contrary to the philosophy of CE, and yet those organisations involved in the case studies claimed to be practising it.

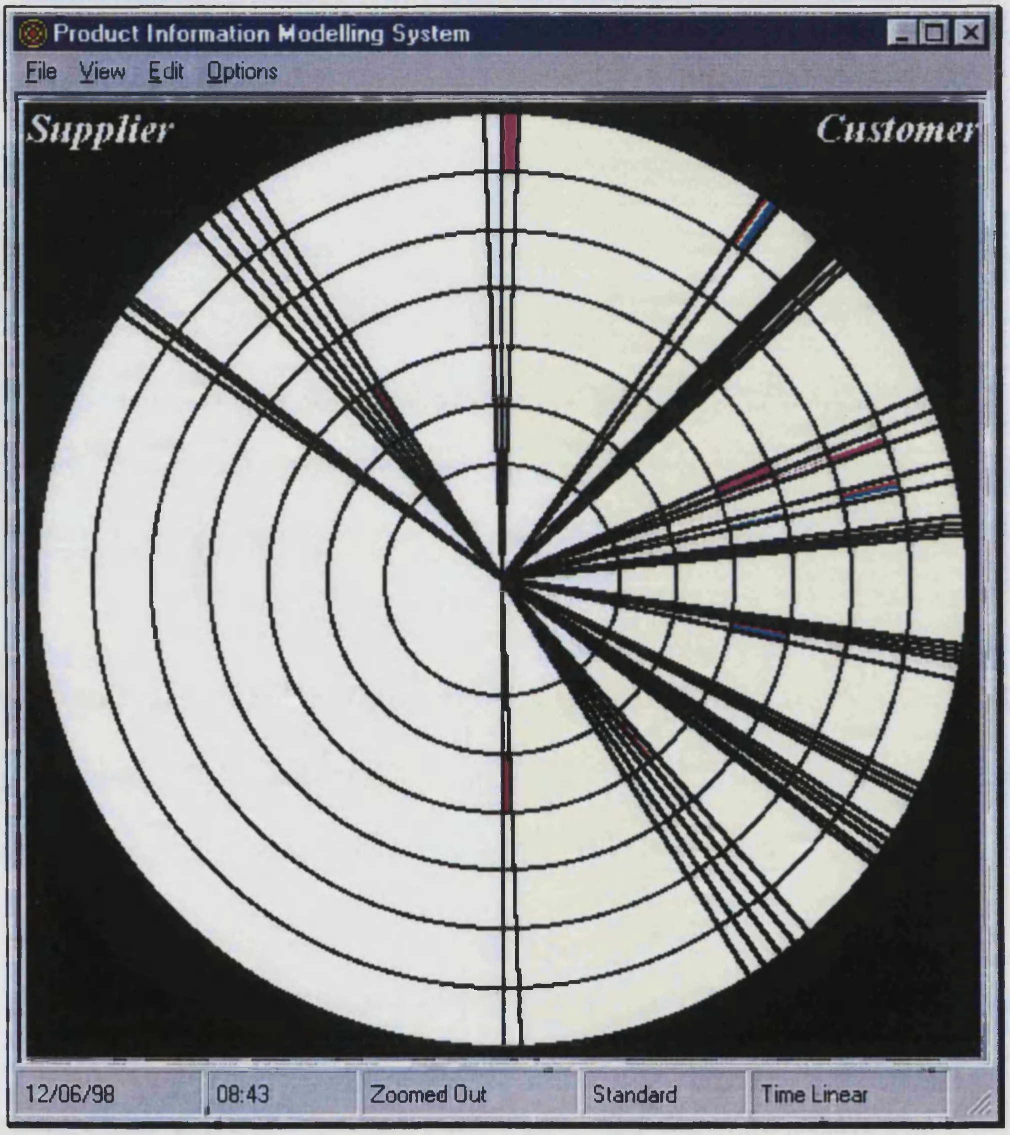

Figure 6.7: PIMS Model for Case Design Project A
(Standard Time Linear Display Mode)

The engineering designer involved in case design project A was questioned regarding the above point. Subsequently, it was revealed that the procedures followed in case design project A were not unusual, as 'CE' was frequently only adopted for high volume products or when problems were encountered with what was termed as a '*tricky*' design. If a more concurrent approach had been adopted in the case design projects, however, it is considered that gains could have been realised. For example:

- *Case design project B* - the problems encountered during manufacture, as previously noted, were attributed to the fact that the supplier had been denied information pertaining to the artefact's function and fitness.
  - ➤ Analysis of PIMS models, together with discussions with both the engineering designer and the supplier involved, indicated that this information could have been shared during the embodiment phase of the design process.

Owing to the fact the above design situation was not repeatable, it was only possible to hypothesise what the impact would have been of providing the supplier with information pertaining to the artefact's function and fitness during the embodiment phase of the design process. However, the convergence of the author's, the supplier's, and the engineering designer's opinions led to the assertion that if this had occurred then the manufacturing problems and the subsequent re-design may have been avoided.

Further, owing to the fact that considerable costs had been incurred immediately prior to the necessary re-design (for example, manufacturing fixtures had been made and a large batch of artefacts had been rough-machined), the subsequent modifications to the original design were constrained somewhat and, as a result, not all of the proposed modifications could be implemented. This therefore suggests that if a meeting, similar to the one in which the re-design was carried out, had taken place during the embodiment phase then this may have resulted in improvements in the artefact's quality, cost, manufacturability, and 'time-to-market'.

6.5.6 Communication Media

Informal communications made up a significant number of the total communications that took place in the case design projects. The telephone, for example, was often used when problems were encountered or for the purpose of checking the status of manufacture (as described in Section 5.3.3, this information was viewed by clicking on the various nodes in PIMS models). Such informal communication media, however, were also used for the sharing of more 'vital' information, for example:

- *Case design project B* - a material change was made over the telephone.
- *Case design project C* - a dimensional change was made over the telephone.
- *Case design project D* - a design change was made over the telephone.

In each of the above examples the suppliers (unofficially) implemented the changes prior to receiving the modified detail drawings. In each instance, this reduced the overall product development time by an estimated 2 days; an example of one of the benefits of close supplier relationships.

From analysing the green nodes in PIMS models it was noted that the above changes were documented in the detail drawings, but the rationale for making them was not. Of further significance, it was revealed that the majority of information that had been communicated informally was not documented either; during interviews it was later found that this practice was not unusual. Inevitably, therefore, it would be lost over time and hence its value may never be exploited to its full potential. This documentation deficiency is thought to be owing to many, possibly interrelated, factors that include, for example, a lack of time to document information; a lack of knowledge of what should be documented; a lack of guidelines as to what should be documented; a lack of suitable tools to enable it to be documented[35]; etc.

[35] The problem may not be owing to the lack of tools, but with the lack of tools to enable this type of information to be accessed, at a later date, in an efficient and effective manner. As otherwise there is little point in storing it in the first instance. This will be further discussed in Chapter 7.

6.6 Discussion

In the first instance, the application of PIMS led to the identification of three types of information that engineering designers may acquire from suppliers, namely random (I_r), requested (I_{rq}), and logical (I_l). These have not previously been identified. With a view to exploiting the information available from suppliers it was suggested that I_r should not be relied upon. However, by focusing on I_{rq} and I_l it was possible to identify additional or sub types of information. Further, it also became evident that the mechanisms by which I_{rq} and I_l may be acquired were not being fully exploited.

In identifying the above deficiencies it is considered that the paths that need to be taken in order to overcome them may also have been highlighted. The most efficacious of these is considered to be the development of guidelines to aid engineering designers in decisions pertaining to, for example:

- What stage in the design process should a supplier be first contacted.
- What level of involvement should a supplier have in the design process.
- What information should or should not be requested from a supplier.
- What information should or should not be shared with a supplier.
- When should information be requested from or shared with a supplier.
- What communication media should be used to share information.

Within those organisations involved in the case studies no such guidelines existed, and it is thought that this may have contributed to the poor exploitation of suppliers. The reasons why such guidelines did not exits may have been owing to factors such as a lack of appreciation of their need or difficulties associated with representing them. For example, Austin *et al* [1996] noted current planning techniques and models "*...cannot represent looped tasks such as design iterations...*", and as a consequence they noted a tendency for "*...design planners to define tasks in the large, ignoring the multiple engineering interactions within each one. A design plan of this nature tends to act as either a straitjacket for designers, inhibiting the design, or to be ignored totally.*"

However, the previous sections have shown that PIMS is, for example, suited to representing looped tasks or iterations; proficient at representing interactions at varying levels of depth or granularity; capable of representing specific types of communication media (Section 4.5.4); and it is applicable to a range of different product development scenarios. Hence, it was considered that the above deficiency could be overcome by employing PIMS to produce guidelines in the form of a synthetic or prescriptive model. Research was therefore undertaken to explore the feasibility of developing interaction guidelines. An overview of this is provided in the following section.

6.6.1 Developing Interaction Guidelines

Efforts in this area were initially focused upon establishing whether similar patterns in information transfer could be identified in similar design projects. In order to aid this, case design project C was selected on the basis that it was similar in nature to the case design project A. By analysing and comparing PIMS models for these two case design projects it was evident that certain patterns could be identified. For example, patterns were apparent in what were previously termed the procedural information flows, such as the exchange of detail drawings or the request for 'best quote and delivery' information.

Having established that patterns could be identified it was evident that that some form of synthetic PIMS model could be developed; that might provide guidelines such as those highlighted above. The realisation of this, however, was considered to be beyond the scope of this present research; inevitably it would demand a greater number of case studies to be undertaken in order to better identify deficiencies in current practices and in turn methods of overcoming them. If such a model were to be developed, however, it is inevitable that design projects would deviate from it to a certain extent. For example, interviews with engineering designers from the collaborating companies indicated that on occasion (owing to time constraints) suppliers had been selected without obtaining a cost quote from them. It is thus believed that such a synthetic model should be amenable to modifications as each design project progresses; this would be possible with a *dynamic* system such as

PIMS. In contrast to the belief Austin *et al* [1996], therefore, who stated that "*For planning to be of real benefit to design and management teams, it must take place before design work commences.*", it is believed planning should take place both before design work commences and as each project progresses.

6.7 Summary

This chapter has presented the application of PIMS to a selection of product development scenarios, and in so doing verified its general applicability (Hypothesis 2). In turn, this application resulted in a number of observations that tended to provide additional confirmation that the information and knowledge available from suppliers is poorly utilised by engineering designers today (Hypothesis 1). Further, in highlighting deficiencies in the way that engineering design is currently practised, avenues by which they could be overcome were also uncovered (Hypothesis 3).

Of further significance, this chapter has provided an insight into an area of design that was not previously well understood; identified a number of new information categorisations; indicated that current design process models may not be sufficient; and highlighted deficiencies in information documentation. Furthermore, it has identified a successful research methodology and thus provided a framework for future empirical research within this new and complex area. PIMS served as a useful mechanism to facilitate data collection both directly and indirectly; by acting as a focal point for further data elicitation and verification during interviews. The observations that were made from analysing PIMS models, in addition to their value *per se*, should also have served to indicate the potential gains that could be made by applying PIMS; a system that can be used by engineers in real design situations.

Finally, it is hoped that this chapter should have served to emphasise the need for organisations to focus on information, and in particular its provision to suppliers. That is if they are intent on exploiting them for the purpose of accruing competitive advantage in today's aggressive global market place. These points will be further emphasised in the following chapter, that addresses and reinvestigates information issues raised during the course of this research over a broad sample range.

Chapter 7.
Supplier and Supplier Information Issues

By way of an investigation over a broad sample range this penultimate chapter expands and generalises pertinent findings that were both presented in previous chapters and identified during the course of this research. This has both enabled them to be further validated and provided a valuable additional insight.

The methodology adopted was that of an extensive questionnaire survey of practising engineering designers and managers within the United Kingdom. This covered issues pertaining to both of the parallel themes of investigation, as outlined in Section 1.7. These issues included, for example, communication and information storage habits; information management procedures; supplier assessment schemes; supplier selection guidelines; supplier interaction procedures; available technology; and engineering designer training.

An overview of the questionnaire methodology is provided together with a discussion of the significant observations and findings. These are discussed both in the context of this research and engineering design in general.

7.1 Introduction

During the course of this research, pertinent findings and observations pertaining to the way that suppliers and their information and knowledge are integrated into the engineering design process were made; a number of these were highlighted within previous chapters. In general, they were founded upon the detailed analysis of both data and PIMS representations of data; that had been collected during a number of 'in depth' investigations. Further investigation of the key findings and issues over a broad sample range was seen to be essential however; it would enable the validation of the earlier findings and provide a good additional insight. Reference to the research literature indicated that questionnaire surveys have been widely used for such broad investigations within the domain of engineering design (Bottle and O'Connor, [1979]; Court *et al*, [1994]; Court *et al* [1997b]; Shuchman, [1981]; Pugh and Morley, [1989]; Raitt, [1985]; Wilkin, [1981]).

The questionnaire methodology, that is ideally suited to gathering data and providing answers to specific research questions, is very efficient in terms of researcher time and effort. It is not without its limitations, however, both in terms of the research issues that can be addressed and, if improperly used, the accuracy of the results obtained. As a consequence, guidance was sought from the vast array of available literature. This included both that from the field of the social sciences and that pertaining to engineering design research that has employed the questionnaire survey methodology, as cited within this chapter.

The following section provides an overview of the questionnaire methodology and the considerations that were made prior-to, during, and after the design of the questionnaire that was used in this research. Subsequent sections present the key findings and observations, and discuss their implications on this research and engineering design in general.

7.2 The Questionnaire Methodology

A high level representation of the methodology adopted in this research is shown in Figure 7.1. From this it can be seen that the research was split into three main phases: pilot study; pre-study; and main study. A discussion of the activities and the key considerations associated with each of these is provided in the sections that follow.

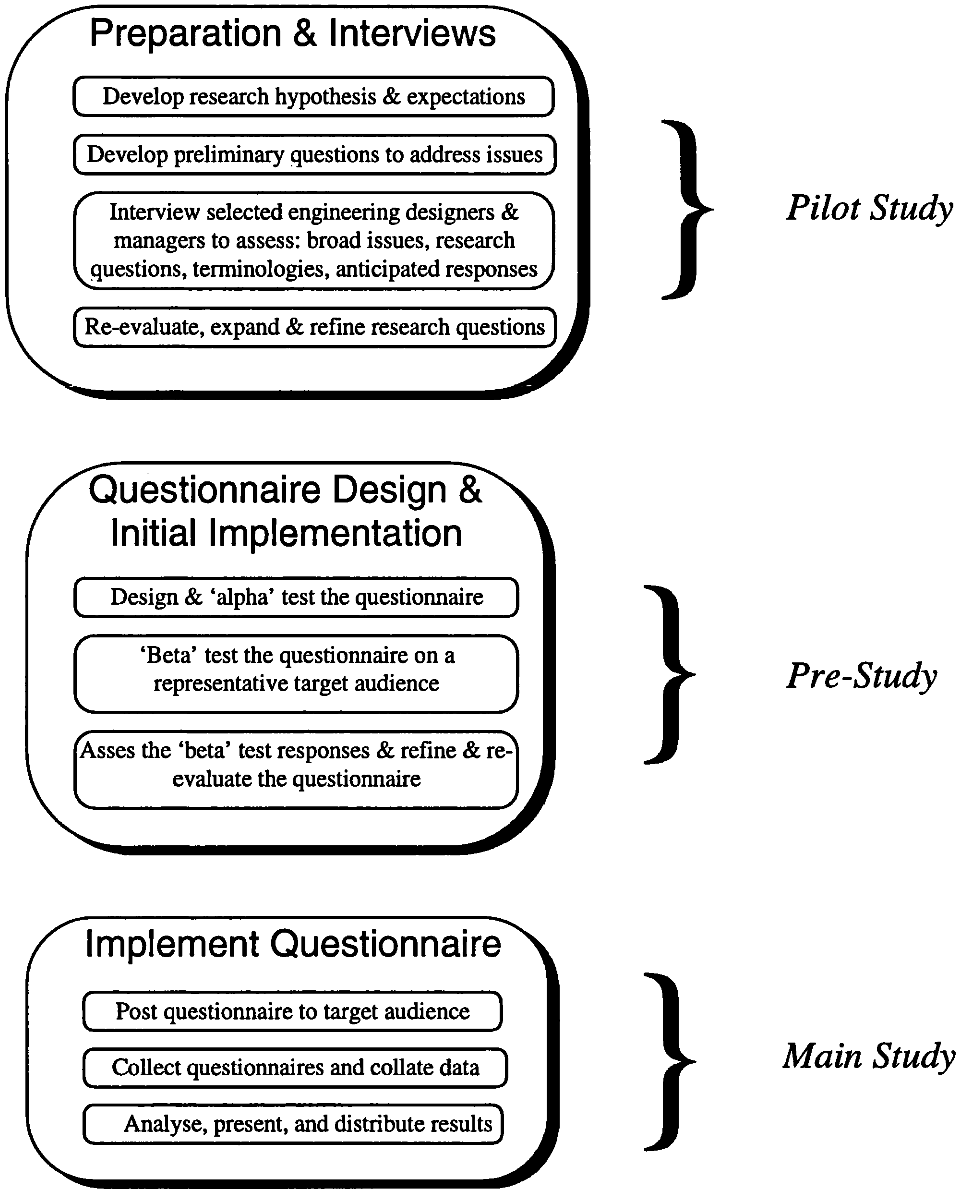

Figure 7.1: The Questionnaire Research Methodology

7.2.1 Pilot Study

It is widely accepted that piloting any empirical research is a pre-cursor to success. This is especially true in the case of questionnaires, where it is not possible, as with interviews say, to gain feedback and adjust the focus of the research as it is being carried out. An initial set of proposed subject areas and questions for the questionnaire were therefore drawn up, and the responses anticipated with a view to establishing whether or not the questions were appropriate to elicit the required information.

As noted by Robson [1995], however, "*Advanced planning and preparation is all very well but there is no complete substitute for involvement with the 'real' situation...*". Hence, interviews with practising engineering designers and managers were also carried out. This rigorous operation was performed in order to gain a broader view of current practices, expand and refine the data collection plans, assess terminologies, and assess likely response categories. The insights gained from this were then employed in the design and development of the pre-study questionnaire, outlined as follows.

7.2.2 Pre-Study

During this phase, the pre-study questionnaire was designed, assessed, and then 'beta' tested by a pilot group of 25 engineering designers and managers. These were selected from a range of personal contacts held by the author and academic members of the University. The feedback from the respondents, together with the information provided during the pilot study phase, were then used to assess whether or not the questions had been appropriately interpreted, the response categories were sufficient, the terminologies were acceptable, the format was acceptable, etc..

The results from the above evaluation were used as a basis for designing the final version of the questionnaire (Appendix 3). The need to pay close attention to this was evident from the research literature. For example, Berdie and Anderson [1974] have noted that "*The inexperienced researcher is likely to be impatient with this preliminary work, which may seem like hair splitting over the meaning of words and other detail. But patience and care in this preliminary work may well make all the difference between success and failure, both in the co-operation of the respondents and in the reliability and validity of the results*". As a consequence, the research literature was consulted in order to obtain guidelines on, for example, the use of open and closed questions, the use of specific and general questions, the phrasing of questions, the terminology and vocabulary of questions, the use of forced response, the use of Likert, Thurstone, Guttman, Q-sorts, Sociometric and other scaling techniques, etc.. Owing to space limitations, however, an overview of the guidelines for just one aspect, namely that of questionnaire format, are presented below. For further details pertaining to other aspects of questionnaire design the reader should refer to the cited literature.

7.2.2.1 Format Considerations

As long ago as 1958 Levine *et al* [1958] reported that "*The appearance of the questionnaire frequently determines whether it is read or discarded. Once the respondent takes the effort to read it, he has some psychological commitment to complete it*". The need for guidance in this aspect of the research was therefore evident, and this was sought from the literature of Berdie and Anderson [1974], Robson [1995], Stacey [1969], Dooley [1990], and many more. Key points from this literature that were considered during the design of the questionnaire have been summarised as follows:

1. *Inclusions* - the first page should include the study title (in bold type), the name of the sponsoring body, and the name and address of the person to whom the form should be returned. A brief note should also be included to solicit an early return of the questionnaire, thank the respondents for their help, and offer to send them details of the findings.

2. *Instructions* - instructions for completing the questionnaire should be brief and clear. Moreover, the questions should be constructed such that the process of answering them is self-evident. For example, putting ticks in boxes is familiar to most respondents whereas circling pre-coded answers is believed to confuse, and hence this method should be avoided.

3. *Appearance* - the questionnaire should be as appealing to the eye as possible. It should look easy to fill and it should provide plenty of space for questions and answers.

4. *Ordering of questions* - initial questions should be easy and interesting. Middle questions should cover the more difficult areas. The last questions should be of

less importance, but still interesting in order to encourage return of the questionnaire. Care should also be taken as the meaning of a question may be altered by a preceding question.

5. *Grouping and numbering of questions* - questions that deal with specific topics should be grouped together. The questions should be numbered and sub-lettered to help in grouping questions on specific issues. The transitions between questions should be made as smooth as possible.

The above guidelines, as with those for the other aspects of questionnaires, were taken as **guidelines** only, as inevitably their effectiveness will vary depending on, for example, the nature of the study or the target audience. This point has been emphasised by Berdie and Anderson [1974] who noted that "*Of prime importance is recognition that some tactics are appropriate while others are inappropriate, depending on the particular sample and study*". In turn this re-emphasises the importance of the pilot and pre-study phases of the research, in which invaluable insights may be gained into the subject area and the likely responses.

7.2.3 Main Study

Having developed and refined the questionnaire, during the vital pilot and pre-study phases, it was then distributed to the target audience. Assistance[36] in this phase of the research was provided by the UK Institution of Engineering Designers (IED).

The IED provided the contact names and addresses for 990 of their members, especially chosen to cover the whole range of their membership grading structure. A further 30 respondents were selected from personal contacts held by the author, thus bringing the number of questionnaires distributed to a total of 1020. The response, as outlined below, was obtained by way of pre-paid envelopes that were included with the questionnaire.

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[36] A better response may be obtained if a questionnaire survey is associated with an institution or some other establishment (Berdie and Anderson, [1974]).

7.2.3.1 Response Rate

The response was believed to be good, in that 258 out of the 1020 distributed (25%) were returned and, of those, 231 were found to be usable (23%). This compares to the typical response rate to this type of questionnaire survey of around 5-10% (Court *et al*, [1997b]) and thus indicates the increasing level of industry interest in this area of research.

7.2.3.2 Questionnaire Analysis and Results

The data from the questionnaires were collated and analysed using Version 7.0 of the Microsoft® Excel® spreadsheet package. It has only been possible to include certain of the results from the analysis within this thesis[37]. These have been categorised under the following main headings and are presented within the sections that follow:

- Background findings.
- Involving suppliers.
- Standard supplier literature.
- Managing supplier information.
- Training and resource availability.

7.3 Background Findings

Invariably, the nature of customer-supplier relationships and the way that supplier information is handled is dependant upon not only those persons involved, but on the organisations in which they work and the design activities undertaken. The questionnaire targeted what was believed to be a good sample range, and this is substantiated below.

7.3.1 Type of Respondent

During the course of this research it was revealed the engineering designer is not the only type of person who forms, maintains contact, or shares information with suppliers. Moreover, within certain organisations it has been noted that engineering designers may even be prevented from contacting suppliers. In these instances engineering designers often receive delayed and filtered information from persons more senior in the design office hierarchy, such as project engineers and engineering managers (Fechter, [1993]). It was therefore seen to be important for the respondents to cover a representative range of seniority and job descriptions.

It was found that 23% of the respondents were of Designer/Draughtsman status, 27% were Product/Project Engineers, 28% Engineering Managers, and the remaining 22% covered various other engineering related positions ranging from Consultant to Technical Director. The respondents were also found to have considerable experience, with the majority (82%) having over 20 years'.

7.3.2 Nature of the Organisation

In order to establish the nature of the organisations in which the respondents worked, they were classified according to industry sector and as being either small, medium, or large. The classifications of company size vary according to the scheme used, and hence the following definitions (adapted from schemes presented within DTI [1997] and SIC [1992]) were used within this research:

- *Small* - companies with less than 50 employees *and* an annual turnover of less than £5 Million.

- *Medium* - companies that do not fall within the categories of either small or large, as defined above and below.

- *Large* - companies with more than 200 employees *and* an annual turnover greater than £50 Million.

It was found that the above sizes were well represented; 31% of the respondents worked in small companies, 38% in medium companies, and 31% in large companies.

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[37] Further results are available in Boston *et al* [1998a] & [1998c].

The industrial sectors in which the respondents carried out their design activities were divided into 10 key areas that were represented as follows: 11% in aerospace, 1% in agriculture, 9% in automotive, 9% in construction, 7% in defence, 36% in manufacturing, 8% in oil, 6% in power, 11% in process, 3% in utilities (gas, electric, and water), and 21% in various other engineering related sectors.

7.3.3 Design Activities

In order to establish the nature of the design activities undertaken by the respondents, the 'original/adaptive/variant' classification was utilised. This, as described in Section 2.3.3, was proposed by Pahl and Beitz [1984].

The questionnaire findings show that 89.5% of the respondents were involved in original design, 89.5% in adaptive design, and 83.5% in variant design. In addition, only 4.5% were involved solely in original design, 3.5% solely in adaptive design, and 3.0% solely in variant design activities. A full breakdown of these results can be seen in Figure 7.2.

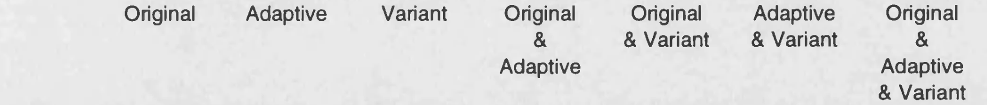

Figure 7.2: Involvement in Design Activities

Numerous researchers have attempted to establish the extent to which engineering designers undertake the various types of design activity in the past. A selection of these are presented in Table 7.1 and discussed below.

Researchers	Design Activity		
	Original	*Adaptive*	*Variant*
Pahl and Beitz [1994]	25 %	55 %	20 %
Black and Shaw [1991]	33 %	92 %	33 %
Court [1995]	84 %	60 %	38 %

Table 7.1: Comparison of Design Activity Research Findings

With reference to the results and discussions presented by these researchers (Table 7.1), it is apparent that a certain amount of confusion is present. For example, Court [1995] suggested that the results presented by Pahl and Beitz [1984] were flawed; Court believed that the results presented by Pahl and Beitz implied that engineering designers only undertake one type of design activity. It is considered, however, that Court may have misinterpreted these results when drawing comparisons between them.

The above assertion is based on the fact that the questionnaire survey undertaken by Court (and possibly Black and Shaw [1991]) could only enable elicitation of <u>involvement</u>[38] in the various types of design activity and not the actual <u>level of involvement</u>[39]. The results of the former may total[40] over 100% whereas the results of the latter would in fact total 100% and hence comparisons should not have been drawn between them. Further, the results dealing with the 'level of involvement' give a more precise indication of what engineering designers actually do, and thus they are considered to be of greater value. For example, if the majority of design work undertaken is either adaptive or variant (redesign), then focusing research attention on both storage and reuse of information would be a viable option.

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[38] Whether or not respondents were involved in each of the design activities.

[39] Division of time that the respondents spent in each of the design activities.

[40] Summation of the normalised values for Original, Adaptive, and Variant.

As it is not known for certain if any of the results presented above pertain to the 'level of involvement', the establishment of this was thought to be an important consideration. Moreover, it was believed that the inclusion of this within the questionnaire would also enable overall generality to be established. The respondents were therefore requested to indicate their organisation's 'level of involvement' in each of the three types of design activity. By summing the percentage levels for each of the respondents the results shown in Figure 7.3 were obtained. Clearly, they differ somewhat to those pertaining to simply the 'involvement' of engineering designers in the various design activities, as presented in Figure 7.2 above (89.5% Original; 89.5% Adaptive; 83.5% Variant).

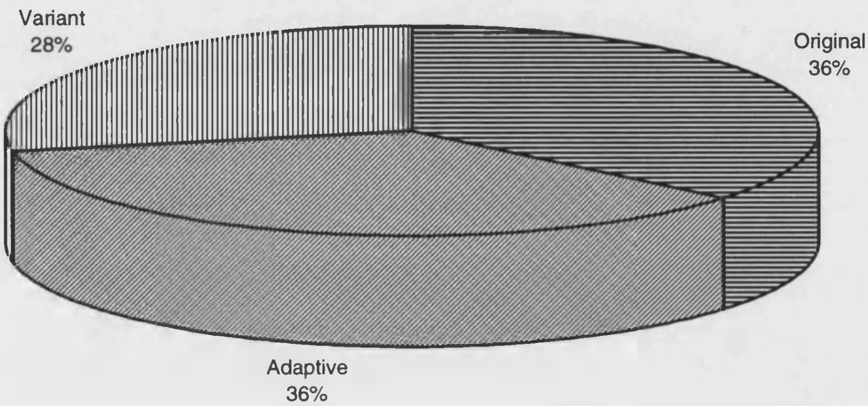

Figure 7.3: Level of Involvement in Design Activities

In addition to throwing light on the findings of previous researchers, the above discussion should have served to emphasise the rationale behind the considerable effort that was taken in both the design of the questionnaire and the interpretation of the results. The more significant of these are presented and discussed in subsequent sections.

7.4 Involving Suppliers

In view of the changes that are taking place in the way that engineering design is practised (Chapter 1), it is considered that decisions pertaining to the selection and subsequent integration of suppliers will become increasingly important to those seeking to accrue competitive advantage. It was thus seen to be important to focus upon issues that may influence how suppliers are selected and integrated into the engineering design process.

7.4.1 Supplier Selection

It has been noted previously that engineering organisations are becoming increasingly reliant upon suppliers for the provision of 'information and knowledge' throughout the engineering design process (Section 1.1). It is therefore clear that they should be taking this into account within their supplier assessment schemes. In turn, this may demand the implementation of formal procedures and mechanisms to enable the 'information and knowledge' previously obtained from suppliers to be evaluated and fed back into these schemes. There would however seem to be few internal barriers to this, as the survey revealed (Figure 7.4) that the relationships between engineering and purchasing departments were below par in only a minority of the organisations in which the respondents worked.

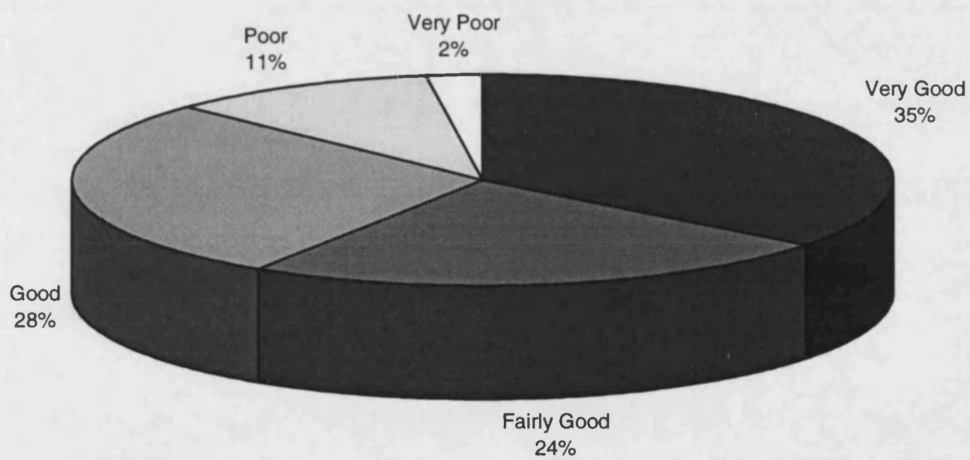

Figure 7.4: Perceived Engineering/Purchasing Relationships

Apart from the 'satisfactory' nature of engineering/purchasing relationships, the survey has indicated that many organisations may be making sub-optimal or inappropriate decisions on supplier selection. Evidence of this is provided as follows:

- The survey revealed that 67% of the organisations in which the respondents worked used supplier assessment schemes. And, where such schemes existed, it was found that 86% of them took account of the 'information and knowledge' previously obtained from suppliers, and 77% of these employed formal vetting procedures to do so. This means that less than 44% (77% of 86% of 67%) of the organisations used supplier assessment schemes that formally considered the 'information and knowledge' previously obtained from suppliers. Further, during the course of this research it has been noted that such schemes may only give a weighting of around 1 or 2% to this factor[41]. In general, they tend to concentrate on quantifiable factors, such as cost, quality, and delivery reliability (Ellram, [1990]).

The above is corroborated by other work which shows that lists of approved suppliers, a frequent output from supplier assessment schemes, may not necessarily represent the most appropriate suppliers from the perspective of engineering designers (Wijnstra and Stekelenborg, [1996]). Not all organisations produce these lists, however, and even less appear to make them available to their engineering designers. This survey, for example, showed that lists of approved suppliers that explicitly stated the <u>nature of the service</u> that the suppliers were approved for were found to be in place within only 53% of the engineering departments in which the respondents worked.

It should be apparent from the above that many organisations may be making sub-optimal decisions on supplier selection. As a consequence, engineering designers working within those organisations may be making poor use of the 'information and knowledge' available globally from suppliers; this reinforces Hypothesis 1.

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[41] This observation was based on an analysis of assessment schemes used by those organisations that collaborated in the detailed case studies; as highlighted in Sections 3.4, 6.2, and 6.3.

7.4.2 Supplier Integration

It was noted in Section 2.4 that the adoption of practices such as CE have tended to call for the involvement, within the preliminary phases of the design process, of all parties who can bring to bear expertise upon a design. The pros and cons of this were also highlighted, and from these it should be apparent that it may <u>not</u> always be appropriate to involve all parties at the concept phase. However, if an inappropriate decision is made (as evidenced in Section 6.5.5), it may result in the loss of potential benefits or worse still the total failure of a product. It was thus seen to be important to establish the level of support that engineering designers receive in these design decisions. This, as outlined below, was gauged according to the availability of formal <u>guidelines</u> and the availability and nature of <u>design process models</u> within the organisations in which the respondents worked.

- *Guidelines* - it was revealed that less than one third (32%) of the respondents had access to formal guidelines to aid them in decisions such as when to contact suppliers, when to involve them in the engineering design process, or what their level of involvement should be. It is possible to view this figure as both encouraging and disappointing, but it does show the extent of additional things that may need to be done to make complete CE credible.

- *Design process models* - more encouragingly, almost two thirds (62%) of the organisations in which the respondents worked had an official design process, and 57% of these explicitly took into account communications with suppliers. Yet, when viewed as a percentage of the overall total, only just over one third (35%) of the organisations in which the respondents worked had design process models with the potential to aid engineering designers in their decisions on supplier interaction. This may however be an omission of concern, as the vast majority of the respondents who had access to these design process models found them of value when interacting with suppliers (Figure 7.5).

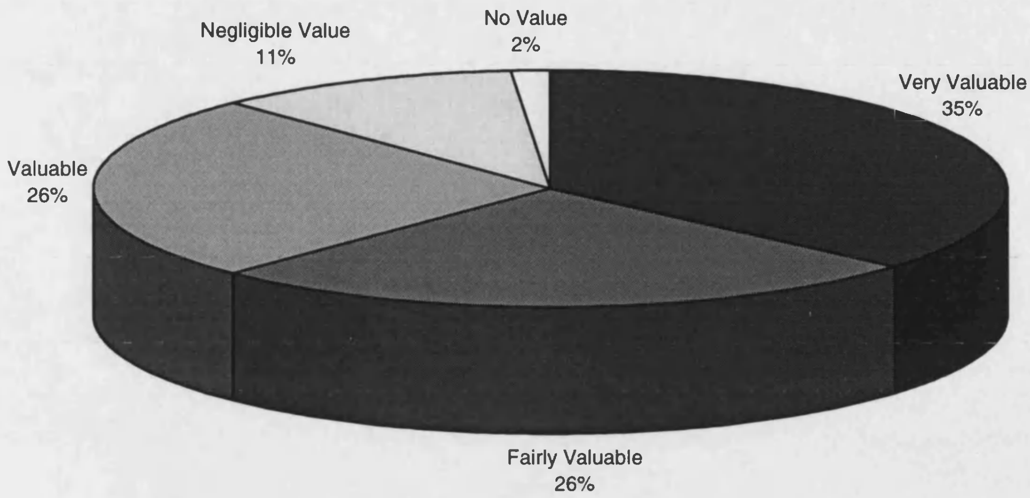

Figure 7.5: Value of Design Process Models for Supplier Dealings

It is therefore apparent that the majority of engineering designers lack support to aid them in their decisions on supplier integration, and inevitably this may result in many sub-optimal decisions and, in-turn, products (Chapter 6).

7.5 Standard Supplier Literature

This section focuses upon the classification and management of standard supplier literature, issues that were discussed and investigated at length in Chapter 3. Because of the increased sample size of the questionnaire survey, however, it was hoped that generality of the pertinent findings could be established. A precursor for this was the use of standard supplier literature by the majority of the respondents. Evidence of this is presented as follows.

7.5.1 Utilisation

During a survey of some 200 engineering designers and mangers, Court *et al* [1994] revealed that standard supplier literature was used by over 91% of them. Hence, it was initially thought that the vast majority of those surveyed within this research would also use it. Confirmation of this was apparent after having analysed the results, outlined as follows:

- It was revealed that standard supplier literature was used within 98% of the organisations in which the respondents worked.

- At a more detailed level it was found that 75% of the respondents had a personal collection of it and 84% stated that, within their organisation, it was also stored within some form of global library.

With the relatively recent advent of electronic supplier catalogues, it was also seen to be important to establish how widespread their use was.

- Within those organisations that stored their catalogues within a global library, the investigation revealed that electronic catalogues were used by 59% of them.

7.5.2 Classification and Management

Within Chapter 3 many deficiencies were highlighted in the way that supplier literature was organised and handled within *the OEM* of study. The comparative results from this survey are presented and discussed below.

- From Figure 7.6 it can be seen that many of the organisations employed classification systems that were not mutually exclusive (Section 3.3.1). Further, it was also revealed that over one third of them used two or more different types of classification 'system' within their global libraries. Hence, with reference to Section 3.5.4, it is apparent that supplier literature may have been dual located within a significant number of engineering organisations.

- Classifying supplier literature according to 'supplier name' inherently demands an engineering designer to have knowledge of what each supplier produces in order for the classification system to be of value (Section 3.5.1). From Figure 7.6 it can be seen that over half of the organisations (54%) that maintained supplier literature within a global library used such a system.

➢ From Figure 7.6 it can be seen that 15% of the organisations that maintained supplier literature within a global library did not classify it. Further, over one third (34%) 'classified' their supplier literature according to its format (catalogue, handbook, datasheet, etc.), and hence effectively it was not classified either.

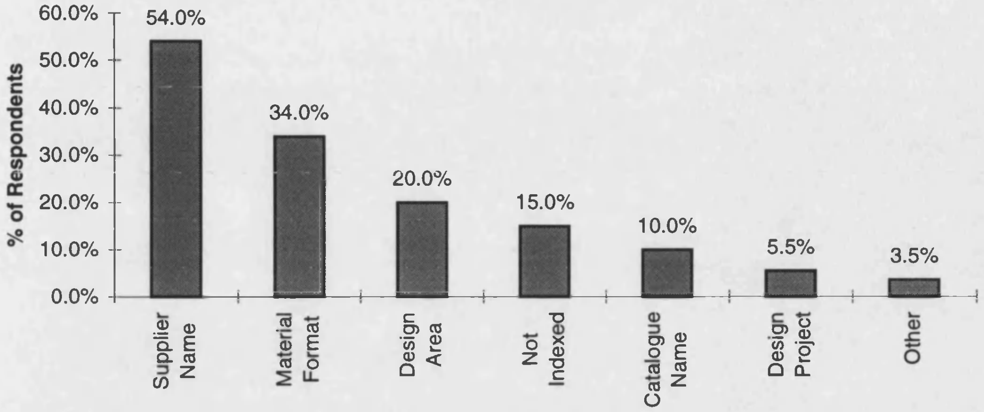

Figure 7.6: Classification Systems for Supplier Literature

With reference to Chapter 3 it is clear that the implications of the above are considerable. For example, the dual location of information may hamper the updating process and in-turn this may result in discrepancies in product versions or pricing. Moreover, inefficient classification systems may not only lead to increases in information access and retrieval times, but they may also result in information being overlooked. Ultimately, this must lead to a reduction in productivity or, worse still, crucial design decisions may be based on incomplete data and assumptions, and they are therefore likely to be sub-optimal.

Within chapter 3, deficiencies were also noted in the way that supplier literature was managed within *the OEM* of study. For example, it was revealed that often its age could not be identified and copious volumes of old information were maintained. The consequences of this were shown to include increased search times, the selection of sub-optimal products, wasted effort, etc.. These deficiencies were largely attributed to a lack of formal procedures for the management of this information source. Hence, owing to the inability to investigate these deficiencies individually, those target by the questionnaire were asked to indicate whether formal procedures existed within their organisation for the management of supplier literature.

> The survey showed that formal procedures for the management of supplier literature were utilised by only just over one third (36%) of the organisations that stored it within a global library.

It thus apparent that many of the deficiencies pertaining to the organisation and handling of supplier literature highlighted within Sections 3.5 and 3.6 may be true for a significant number of engineering organisations. Hence, in addition to confirming that *the OEM* investigated in Chapter 3 was not an isolated case, this should serve to emphasise the need to pay further attention to this area.

7.6 Managing Supplier Information

This section addresses issues pertaining to the handling of information exchanged between the design functions of customers and suppliers engaged directly in product development. This area was previously investigated in some depth within Chapter 6.

7.6.1 Obtaining Information

Within Section 2.4.1 the importance of face-to-face communication within the design and development of new products, and particularly during the preliminary phases, was expressed. However, when suppliers are involved it was noted that the use of this medium may be frustrated by geographic distance. Evidence of this, although not explicitly expressed, was noted in Chapter 6 in the context of the detailed PIMS case design projects. It was thus seen to be important to establish the extent to which geographic distance has effected the nature of communications between the design functions of customers and suppliers engaged in product development. Those targeted by the questionnaire were therefore asked to indicate how many times during a typical working week they used each of a range of different media for obtaining information from suppliers. The results of this, as presented in Figure 7.7, have been arranged[42] according to frequency of use greater than once per day (5 times per week).

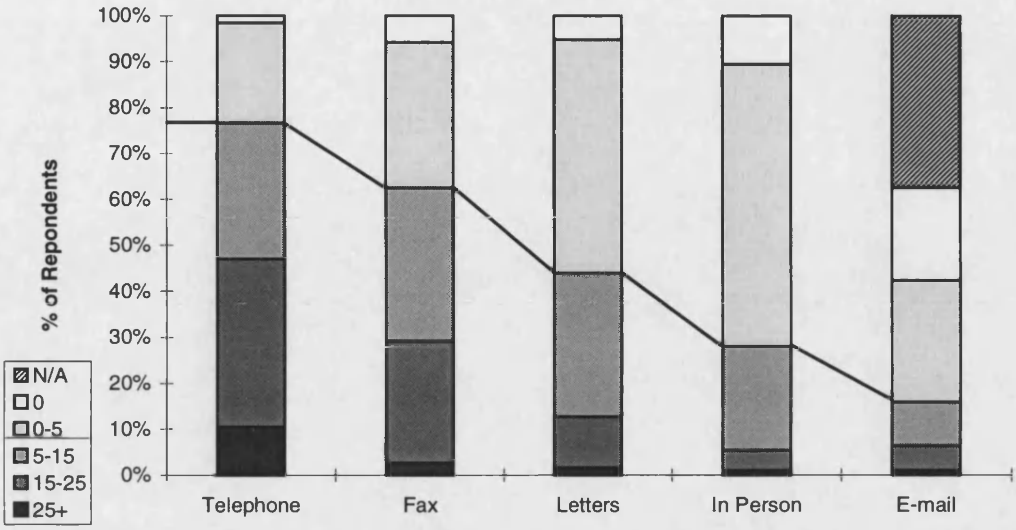

Figure 7.7: Supplier Communication Frequency for a Range of Media (Per typical working week)

It is apparent, therefore, the telephone is the preferred medium for communicating with suppliers, and hence geographic distance may have had a marked impact upon the all important face-to-face communications.

7.6.2 Predicting Information Requirements

Having undertaken this research it is considered that advance knowledge of what information might be required for a design project would be of considerable value. For example, it may minimise the time spent waiting for information or enable information to be accessed that time would otherwise not allow. It is thought that the ability to obtain this knowledge could be realised by extending the work on pattern recognition using PIMS (Section 6.6.1). Thus, with a view to establishing an avenue for future research, those targeted by the questionnaire were asked to indicate the potential value of a tool that would enable the prediction of what information might

[42] If the e-mail results are manipulated to take into account those who had no access to it this order remains the same.

be required for a design project before starting it. The results of this, as presented in Figure 7.8, clearly show that such a tool is thought to be highly desirable within the domain. This may also serve to emphasise the effort normally associated with obtaining information during the course of a design project and the time spent as a result of not obtaining the right information at the right time.

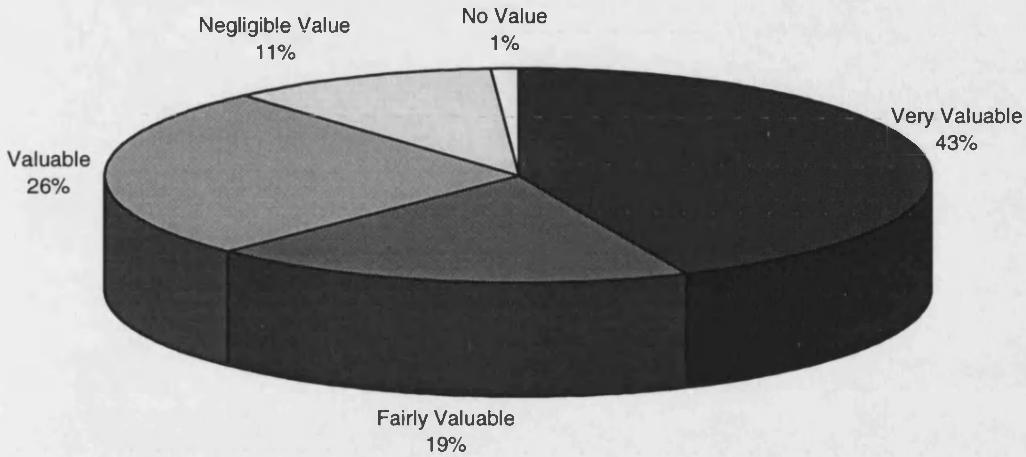

Figure 7.8: Value of a Tool for Predicting Information Requirements

7.6.3 Storage and Record Keeping

From analysing PIMS models pertaining to the detailed case design projects (Section 6.5) it was clear that much information was communicated informally between customers and suppliers (see Section 7.6.1 also). The documentation of this information, however, appeared to be dependent upon the communication media by which it had been obtained. Thus, with a view to establishing the extent to which this problem[43] was prevalent within industry, those targeted by the questionnaire were asked to indicate, for each of the media outlined in Section 7.6.1, how often they stored the information that they had obtained from suppliers. The results of this,

[43] As noted in Section 7.3.3, almost two thirds of design is non original (re-design). Hence, the storage of design data should be a key priority for the vast majority of individuals and organisations alike.

as presented in Figure 7.9, have been arranged according storage frequencies above the level of 'Occasionally'.

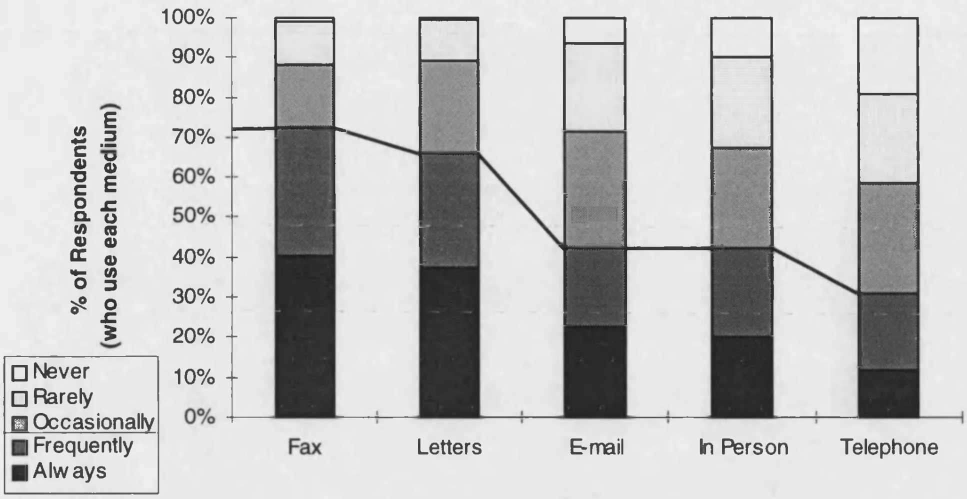

Figure 7.9: Storage Levels for Supplier Information

It is thus clear, but perhaps not surprising, that engineering designers are less likely to document information that has been communicated verbally. Consequently, it will be lost over time and its value may never be exploited to its full potential. This is a distinct problem owing to the fact that the telephone is often used for sharing key or vital information (Section 6.5.6). Further, it is apparent that there is a mismatch between the way that information comes into the design office and the ability to store it; Figure 7.7 and Figure 7.9 have the telephone at opposite ends of the scale.

The root cause of the above problem, however, is believed to lie not only with the lack of tools to enable (both formal and informal) engineering design information to be recorded in a timely manner, but with the lack of tools to enable it be retrieved, at a later date, in an efficient manner. Therefore, with a view to providing a direction for future research and development by establishing the current baseline for information storage, those targeted were also asked to indicate where they typically stored the information that they had obtained from suppliers. The results of this, as shown in Figure 7.10, indicate that the majority of engineering designers tend to store the information received from suppliers in a project file.

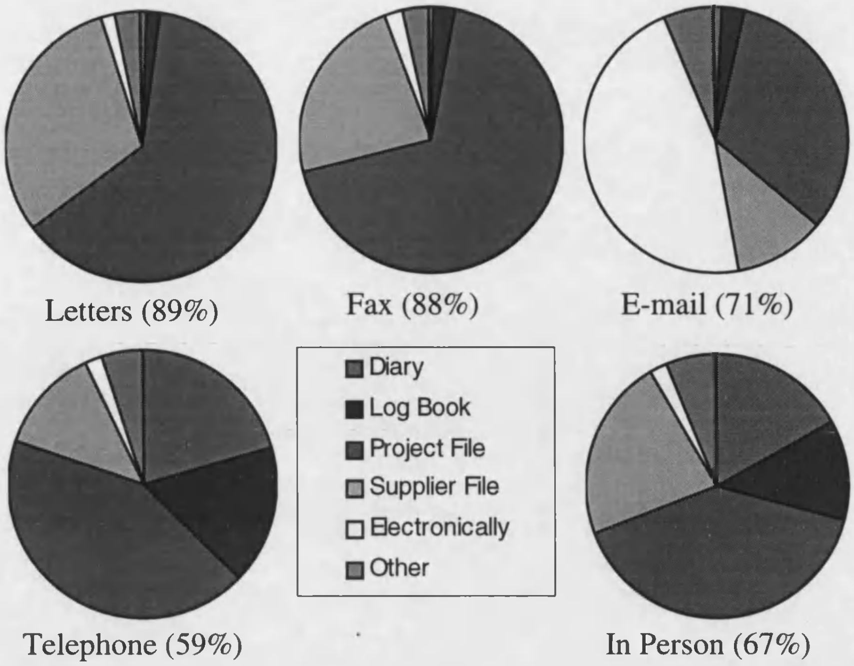

Figure 7.10: Information Storage Locations Versus Communication Media

It was also noted that a significant number of the respondents (16% to 20%) stored supplier information in more than one location, and this appeared to be particularly prevalent for that information which had been communicated informally. This may be a further indication of both the 'problems' associated with the documentation of this information and the need to focus future research attention upon it.

7.6.4 Awareness and Dissemination

Organisations are increasingly having to incorporate new and diverse technologies into their products in order to accrue competitive advantage (Section 1.1). The increasing volumes and sources of information available to engineering designers, however, must ultimately create a barrier to their identification (Workman, [1995]). Hence, with a view to aiding the information overload situation, it was seen to be important to identify the key sources of this information. Those surveyed were therefore asked to indicate how valuable (on a scale of 5 to 1; 5 being very valuable, 1 being of little or no value) they had found each of a range of different information sources for making them aware of new products, materials, services, or technology advancements in general. The results of this, as presented in Figure 7.11, have been arranged according to the % of respondents who gave them a value rating of 3 or above; this could be considered to be a good threshold of useful information sources[44].

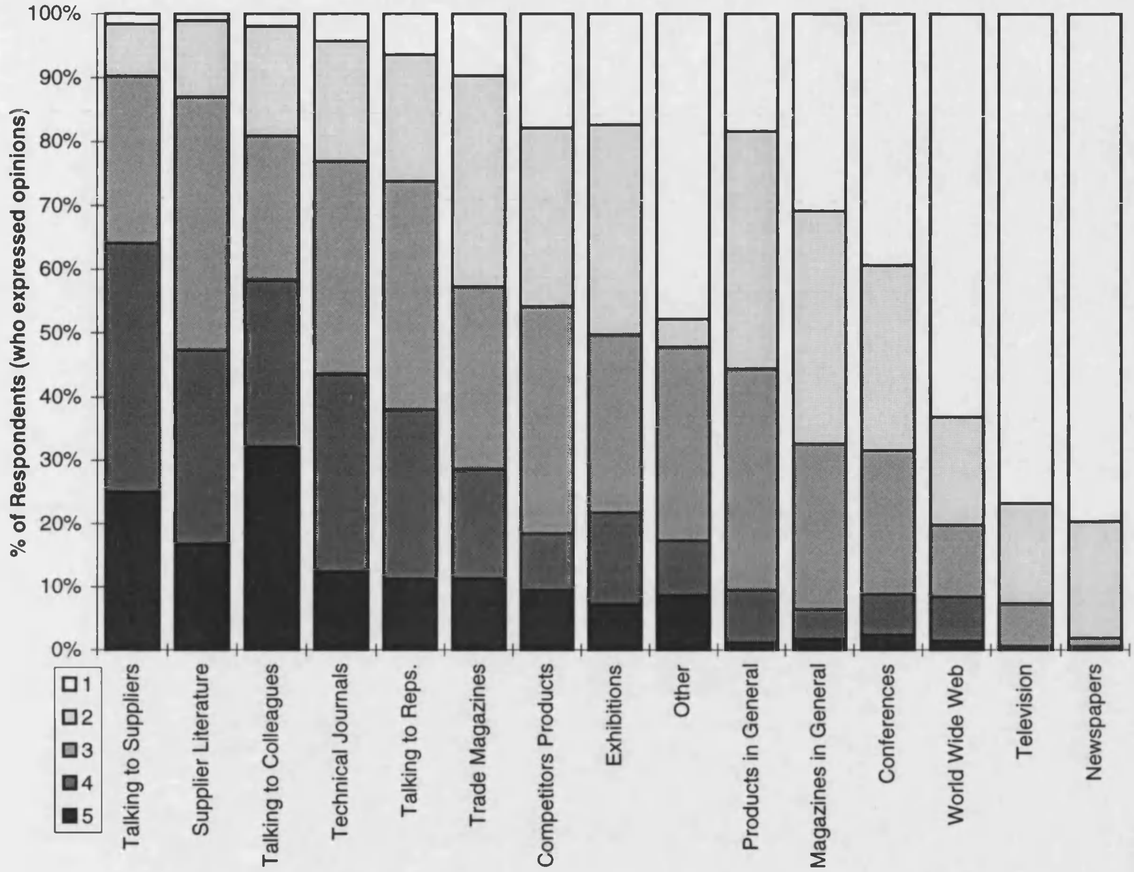

Figure 7.11: Value Rating of Information Sources for Awareness Purposes[45]
(5 being very valuable, 1 being of little or no value)

The results shown in Figure 7.11 should serve to re-emphasise both the role that suppliers and inter-personal communication channels play in the engineering design process, and the need for organisations to pay close attention to the customer supplier information interface. In contrast, it was found (Figure 7.12) that on average less

[44] These key sources were identified as a result of interviews with engineering designers and managers during the pilot study phase.

[45] Not all of the respondents expressed an opinion on every information source and hence the *% of Respondents* relates, for each information source, to those respondents who did express an opinion.

than half of those surveyed frequently or always share the information obtained from suppliers with their colleagues, and almost a quarter never or rarely did so.

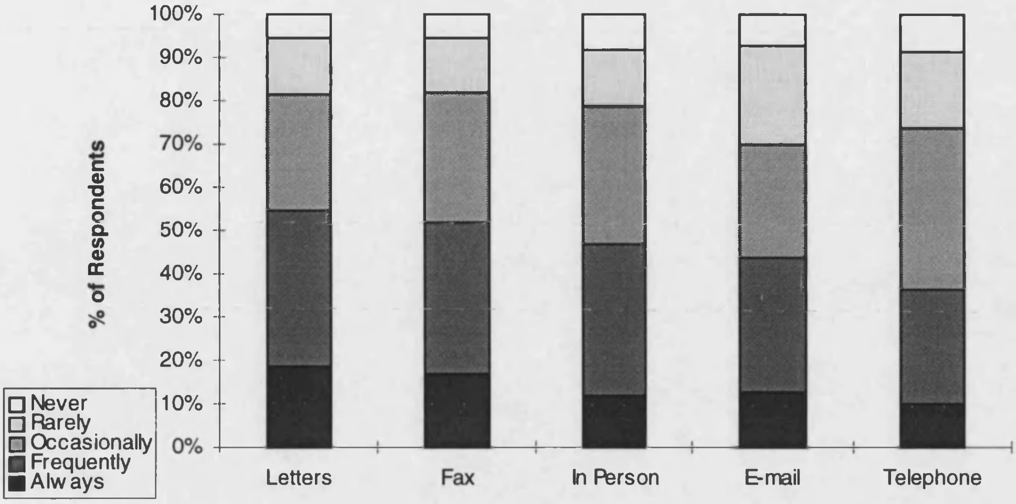

Figure 7.12: Levels of Supplier Information Dissemination

Of further note, it is apparent from Figure 7.12 that the level at which supplier information is shared is largely independent of the media by which it was first obtained. However, the telephone does rank slightly lower than the other media.

7.6.5 Provision of Information to Suppliers

Within Section 6.5 it was shown that the suppliers involved in the case design projects may have been denied the opportunity of interjecting their expertise into the design process because the engineering designers failed to provide them with sufficient information pertaining to the function and fitness of the design projects being undertaken. In turn, this failure was attributed to factors that included a lack of guidelines pertaining to what information should be shared with suppliers, and a lack of appreciation of the benefits of providing suppliers with information over and above that required to facilitate manufacture. These two aspects were addressed by the questionnaire; the resultant findings are presented as follows:

- *Benefits* - those surveyed were asked what they thought the effect would be (on the quality of a design) of giving the supplier access to more information about the design project being undertaken within their company. The results of this (Figure 7.13) indicate that the respondents opinions were fairly mixed. This was also found to be the case when cross correlating the results according to the types of suppliers that the respondents stated their organisations were involved with, namely partners or early involved, design to specification, design and make to specification, make to drawing, standard component, and raw material. However, when cross correlating the results against organisational size, it was found that over two thirds of those who worked in Large organisations stated that increased information provision to suppliers would have either a very or a fairly good impact on the quality of the design, with none stating that it would have a poor or very poor effect.

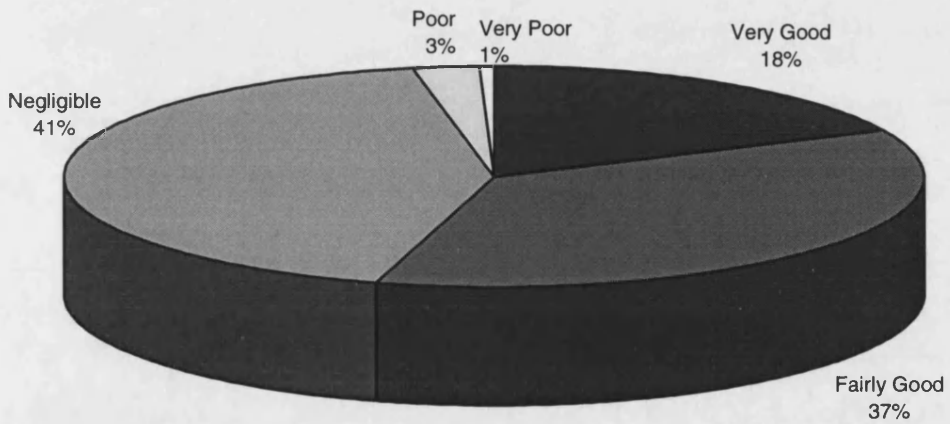

Figure 7.13: Effect on Design Quality of Giving More Information to Suppliers

- *Guidelines* - with regards to the availability of formal guidelines pertaining to what information should be shared with suppliers during a design project, it was revealed that only 35% of the organisations in which the respondents worked had them in place.

In view of the findings presented in Chapter 6 it is apparent that this area is worthy of further attention.

7.7 Training and Resource Availability

With a view to throwing additional light on the research presented within this thesis, the questionnaire also aimed to elicit both the level of 'information' related training that engineering designers have received and the availability of computing resources within engineering organisations. The results of this are presented as follows.

7.7.1 Training

In view of the aforementioned changes in working practices and the volumes of information that engineering designers and managers have to deal with today, it was thought appropriate to assess the general level of training that they have received in respect of these areas. The results of this, as shown in Figure 7.14, indicate that the majority of the respondents have received no training in information retrieval, storage, and, more significantly, classification. Yet, in view of the findings previously presented in relation to, for example, the time that engineering designers spend trying to locate and access information, the documentation of information received from suppliers, and the classification of supplier literature, it is clear that this situation needs to be rectified.

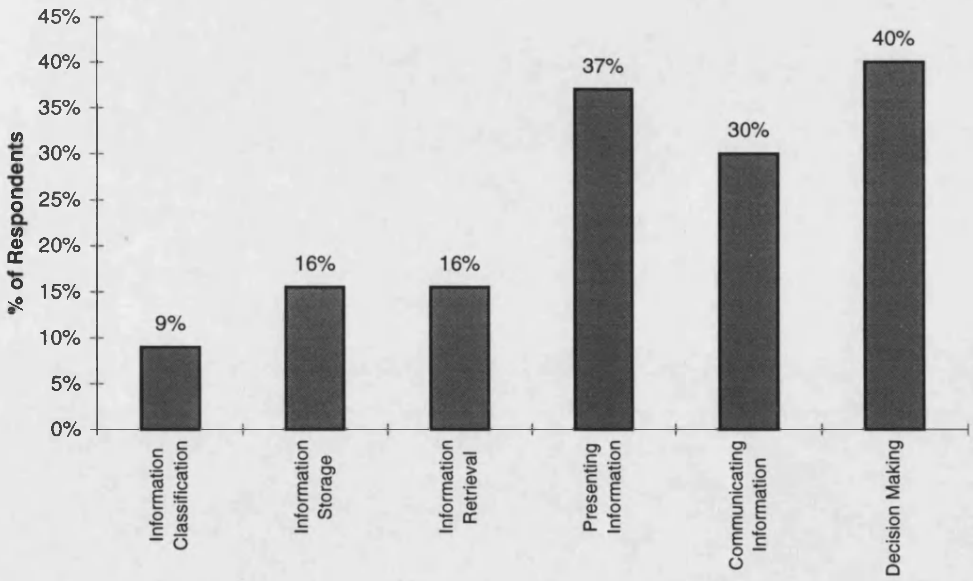

Figure 7.14: Respondent Training

7.7.2 Resources

Within previous chapters it has been noted that the computer, together with emerging communication solutions, will have a profound effect on the way that engineering design is practised in the future. It was therefore seen to be important to establish the availability of such resources at this moment in time. The results of this, as shown in Figure 7.15, may also lend further explanation to a number of the findings previously presented.

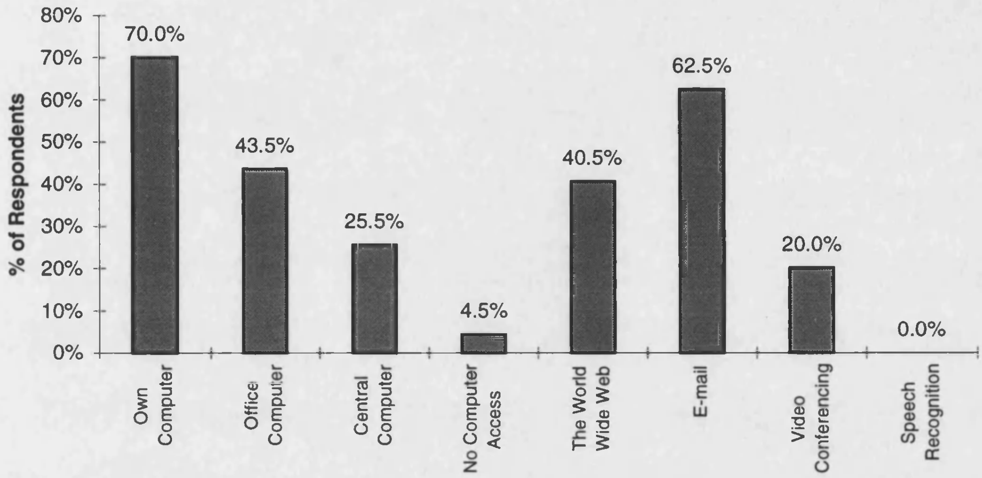

Figure 7.15: Available Computing Resources

The above findings may also serve to highlight that 'available' resources may not necessarily meet the needs of engineering designers. For example, the documentation of information communicated verbally was previously noted to have been problematic and yet it is clear that speech recognition systems have not caught on in the domain. Similarly, it is apparent that e-mail is available within a significant number of engineering organisations and yet it is not widely used for communicating with suppliers (Section 7.6.1).

7.8 Summary

This penultimate chapter has provided an overview of the questionnaire survey methodology and presented and discussed the results that emanated from its application to over 230 practising engineering designers and managers in the UK.

The audience was shown to be representative, being split, in roughly equal proportions, between designer/draughtsmen, project/product engineers, engineering managers, and others, that ranged from Consultant to Technical Director. The nature of the respondents' organisations and the design activities undertaken within them were also shown to be from a representative sample range.

It was shown that approximately two thirds of the organisations in which the respondents worked had no formal procedures in place for the evaluation of the information and knowledge obtained from suppliers. A similar number also failed to provide their engineering designers with guidelines pertaining to the integration of suppliers into the engineering design process. Hence, in view of the recent changes in working practices and the subsequent demands being placed upon suppliers, it is likely that many organisations may not be exploiting suppliers to their full potential.

It was also revealed that many organisations may have paid insufficient attention to the management of standard supplier literature; an information source that was shown within Section 3.2 to be crucial within the design and development of new products. This lack of attention was found to be particularly so in the context of classification. This, however, is an area of great concern when considering the impact that classification has on, for example, information retrieval times and the fact that previous chapters have shown that engineering designers spend considerable amounts of time trying to locate and access information.

A further aspect addressed by this chapter was that of the management of information exchanged between the design functions of customers and suppliers engaged directly in product development. Within this it was shown that the telephone is the most widely used medium for communicating with suppliers and yet the information obtained via this medium was the least likely to be documented by engineering designers. Of further concern, despite the fact that a significant number of engineering designers never or rarely shared the information obtained from suppliers with their colleagues, inter-personal communication channels were shown to be the best means of obtaining information about, for example, new products, services, or technologies.

Of great significance, this chapter has confirmed certain of the findings presented in previous chapters and in so doing enabled the hypotheses of this research to be fully addressed. Further discussion of this will be provided in the following chapter, that presents the overall conclusions to this research together with its limitations and its possible future directions.

Chapter 8. Conclusions and Future Research Issues

This research has aimed to provide an understanding of the issues surrounding the engineering designer and information today. It has focused on the flow of information within and between the design functions of customers and suppliers engaged in product development. This is an area of increasing importance that has received only limited attention elsewhere.

This final concluding chapter will draw upon the research undertaken by the author along with that of others presented throughout this thesis. Its aim is to address the original hypotheses of this research, as presented in Section 1.6. It will also consider the limitations of this research and the various avenues for its further progression.

8.1 General Conclusions

As the millennium approaches, the role of information for business organisations in general will become more and more important. This is particularly so in the domain of engineering design, where the diversity and explosive pace of developments in materials, components, production techniques, analytical methods, CAD strategies, etc., is having a marked affect on the way that information needs to be handled. Engineering organisations, in an effort to maintain competitiveness, are having to focus their efforts solely on their own core technologies and they are thus subcontracting out increasing amounts to suppliers. In turn, engineering designers are losing touch with developments in areas other than their own and as a consequence they are having to rely on suppliers to provide both information and knowledge.

At a macroscopic level, research into areas such as logistics or supply chain restructuring appears to have caught up with the pace of change outlined above (Harland, [1995]). Yet, at the level of the engineering designer research appears to be virtually non existent, and as a consequence there are a distinct lack of guidelines or techniques to aid the integration of suppliers and in particular their information and knowledge into the engineering design process. Therefore, in order to improving the situation, this research was focused on understanding the nature of information interactions that take place within and between the design functions of customers and suppliers engaged in product development. This led to the proposal of three hypotheses for this research which, if satisfied, would provide improved support for engineering designers throughout a vital part of their day-to-day activities.

Hypothesis 1

- The wealth of information and knowledge available from suppliers is poorly utilised by engineering designers.

Hypothesis 2

- The utilisation and exchange of information between customers and suppliers during the product development process can be modelled.

Hypothesis 3

- These models can be usefully used in a design tool to help integrate suppliers into the engineering design process.

This research has been largely progressed along two parallel lines of investigation. The first was focused upon the organisation and handling of standard supplier literature, in a variety of formats. The second was focused upon modelling the information interactions within and between the design functions of customers and suppliers engaged directly in product development. The methodology adopted was based on the analysis of empirical data that was collected via techniques such as interviews, questionnaires, direct observation, involved observation, and even a number of bespoke methodologies that were developed to meet the demands within this new and complex area. The main conclusions from this research are summarised in the sections that follow.

8.1.1 Standard Supplier Literature and its Life-Cycle Management

A review of the literature pertaining to the utilisation of standard supplier literature showed that it both plays a significant role and is heavily relied upon within the engineering design process (Section 3.2). Conversely, however, it was noted that research beyond this was rather limited, particularly in the context of how it is and how it ought to be managed within design functions. An extensive investigation was therefore carried out into the way that this information source was organised and handled within a medium sized OEM. In general this revealed that an array of deficient 'systems' were used for classifying it and there were no formal procedures in place for its life-cycle management.

Significantly, however, the above deficiencies resulted in the wastage of time, money, and effort, and the utilisation of sub-optimal products and information. Their investigation over a broad sample range was therefore seen to be essential, and this was achieved by way of a questionnaire survey of over 230 practising engineering designers and managers within the UK. The results of this, as presented in Chapter 7, verified the generality of many of the earlier findings (Hypothesis 1), and in so doing highlighted a number of areas in need of attention from both organisations and future research.

8.1.2 Development of the Product Information Modelling System

The need for tools to enable the engineering design process to be understood from an information exchange standpoint, particularly when suppliers are involved, was expressed within Chapters 1 and 2. A number of formal modelling techniques were therefore analysed and evaluated for their applicability to this area of research (Chapter 4). During this evaluation, however, it was revealed that none of them were ideally suited. Thus, with a view to overcoming this shortfall, a new modelling technique termed the Multi-functional Information Model (MIM) was developed. This was subsequently applied to case study data pertaining to the information interactions that took place within and between design functions of customers and suppliers engaged in product development (Hypothesis 2).

The ability to model these information interactions, however, was not found to be sufficient to enable the needs of this research to be fully met. This was because the collection of good quality real information interaction data was frustrated by a lack of suitable research techniques and instruments. In order to help overcome these difficulties, and in turn enable the further validation of Hypotheses 1 and 2 and the attainment of Hypothesis 3, the Product Information Modelling System (PIMS) was developed.

PIMS, as outlined in Chapter 5, was a software package that integrated the MIM technique with various new information and information interaction categorisations. It was developed in such a way as to both extend the capabilities of the MIM technique and to aid the collection of good quality case study data. This was achieved by designing the user interfaces such that they would, for example, both prompt the user for appropriate data and enable it to be entered in a timely manner. It was shown to be a flexible and dynamic information modelling system that was capable of representing an array of information interaction types.

8.1.3 Validation of the Product Information Modelling System

Within Section 5.4 PIMS was evaluated against the criteria that were drawn up in Section 4.4.1 for the evaluation of the formal modelling techniques. During this evaluation it was shown that PIMS was able to meet these criteria and, in turn, that it was applicable to this research.

In order to validate PIMS it was installed within a number of collaborating companies and applied to a range of different design situations (Chapter 6). This resulted in a set of fully documented case studies and models, pertaining to the information interactions that took place within and between the design functions of customers and suppliers engaged in product development (Hypothesis 2).

Analysis of the models and the data that were collected both within PIMS and during interviews with the various parties involved provided a good insight into an area of design that was previously not well understood. Furthermore, it resulted in the identification of three key mechanisms by which the information and knowledge available from suppliers may be acquired and incorporated into the engineering design process. By focusing on these mechanisms it was revealed that they were not being exploited to their full potential (Hypothesis 1). Yet, in identifying these deficiencies, ways by which they could be overcome were also highlighted and proposed (Hypothesis 3).

Certain of the above findings were further validated by reinvestigating them over a broad sample range by way of the aforementioned questionnaire survey. The survey was also used to investigate a number of additional issues that were uncovered during the course of this research. The results of this showed, for example, that many organisations may be making sub-optimal decisions on supplier selection, that engineering designers were lacking in certain training, that the communication and documentation of supplier information was deficient, etc.. In turn, therefore, these findings added substantial further weight to Hypothesis 1.

8.2 Research Limitations

Owing to the fact that every design and manufacturing situation is different, it is not possible to undertake design research that is completely generic. Yet, by increasing the sample size it is clear that this ideal could be approached. Thus, with this view in mind, a number of the key findings were reinvestigated over a broad sample range. This dual research approach, of detailed case studies followed by an extensive questionnaire survey, is considered to be a strategy of interest; the detailed case studies enabled the key issues to be identified and the questionnaire enabled them to be generalised.

Owing to the complexity and depth of this research, however, it was not possible to re-address each and every research issue with the questionnaire. Hence, certain of the findings, and in particular those that emanated from the application of PIMS, were based solely on small sample sizes. In the context of previous design research, however, these sample sizes were relatively large. Moreover, much of the data collected was validated from a number of perspectives, and it is therefore considered that findings presented were valid within their context.

8.3 Future Research

Within and as a result of this research many areas that were thought to be worthy of research attention were identified. The more fruitful or perhaps challenging of these are outlined in brief as follows.

8.3.1 Information Half-life

The concept of information half life was introduced in the context of supplier literature in Section 3.7.3. It is however believed that this metric could be extended somewhat and, of further significance, brought to bear on engineering design information in general. The ramifications of this, in terms of information utilisation and even storage, could be many-fold. For example, applying this metric to information might affect whether or not it is stored, what format it is stored in, under what classification it is indexed (e.g. a time-based classification), whether it has to be updated before using it, whether it should impact upon a product's risk assessment, etc..

In view of the ever increasing rate of technology advancements it is clear the 'half-life' of information is reducing by the day. Its significance is therefore increasing and to the extent perhaps where it deserves due consideration from further research.

8.3.2 The Life-Cycle Management of Supplier Literature

It should be evident from previous chapters, particularly Chapters 3 and 7, that the 'life-cycle management' of supplier literature is a particularly fruitful area for further research and development.

From the insights gained as a result of this research it is considered that the following suggestions deserve further attention:

- The development of more effective classification systems that;
  - Adhere, where possible, to the principles of classification.
  - Are based on industry standards developed in line with suppliers.

- The development of quality assurance guidelines[46] or systems that;
  - Dictate the effort required to verify information quality.
  - Increase general awareness of information quality issues.

- The inclusion, within supplier literature, of information such as;
  - Its approved quality assurance level or rating.
  - Its production date or even its validity period.

A number of the above suggestions would require co-operation from suppliers and even the industry as a whole. Their implementation, however, could be of considerable benefit to the vast majority of engineering organisations and designers alike.

8.3.3 Information Storage Tools

Within this research it was revealed that engineering designers did not always store the information that they had both created and obtained during the course of a design project. In turn, this was partly attributed to a lack of suitable documentation tools. Yet, before this shortfall can be overcome it is considered that further research is necessary in order to establish the requirements of such tools.

However, a number of *preliminary* requirements, that became apparent after having undertaken this research, have been summarised below:

[46] This concept was introduced in Section 3.7.2.

- The ability to store information rapidly and possibly 'on the move'.
- The ability to store information communicated verbally.
- The ability to store rough sketches and hand-written notes.
- The ability to structure information for timely retrieval.
- The need to provide short and long-term benefits to the user.
- The need for information storage to be a 'natural' activity.
- The need for stored information to be widely accessible.
- The need for certain information to be automatically updated.

The above requirements do not purport to be all encompassing or even accurate, rather, they are intend solely as 'food for thought'.

8.3.4 Design Process Models

A number of established design process models, that were primarily developed in order to aid engineering designers, were presented and discussed in Section 2.3.3. It was noted that these placed limited emphasis on information and communication and, in general, made no provision for the integration of external parties such as suppliers. In view of the increasing demands being placed on suppliers for information, however, it is considered that these omissions need to be rectified (see Section 7.4.2).

Further, it was shown in Section 6.5.5 that a significant number of information interactions may take place after the detail design phase. Hence, if design process models are to serve there purpose more appropriately (or at least in instances when suppliers are involved), it is believed that they need to be extended somewhat to take account of the phases beyond the detail design phase.

8.3.5 Application of PIMS

During the course of this research considerable time and effort was put into the development of PIMS. This was subsequently used to collect and simultaneously model data pertaining to the information interactions that took place in a number of real design situations. In addition to verifying its applicability, the application of PIMS resulted in a number of pertinent observations. As previously noted, however, time constraints restricted both the number of case studies that could be undertaken and the significant further exploration of the observations made from analysing PIMS models.

These observations, however, in addition to their value *per se*, should have served to identify the potential benefits that could be made by further applications of PIMS. Thus, it is believed that this research could be progressed substantially solely by continuing it along its original path. Further, by analysing an increased number of models it is believed that the work undertaken on information transfer pattern recognition could be progressed. In turn, it is envisaged that this might then enable the development of 'synthetic' or prescriptive PIMS models and the prediction of likely information requirements. These capabilities were shown in Chapter 7 to be highly desirable within the design community.

8.3.6 Extensions to PIMS

For the purposes of this research it was only necessary to install PIMS within the collaborating customer companies and not the supplier companies. With the advent of more advanced Internet protocols[47], however, the software could be installed within both the customer and the supplier companies, and the projects' databases could be shared (and updated by both parties) by locating them on a remote network (accessed using the Internet). A pictorial representation of this scenario is shown in Figure 8.16.

In view of the understanding gained from undertaking this research it is considered that the potential benefits of such a scenario could be substantial, both in terms of research and engineering design itself. For example, if PIMS was used rigorously and in real time the models could provide a mechanism to facilitate logical information acquisition (Section 6.5). Hence PIMS, in itself, could prove to be a key

[47] For example, Java™ (from Sun Microsystems) or ActiveX™ (from Microsoft).

facilitator in supplier (information) integration. At present however this is only a notion, but one that is certainly worthy of further consideration.

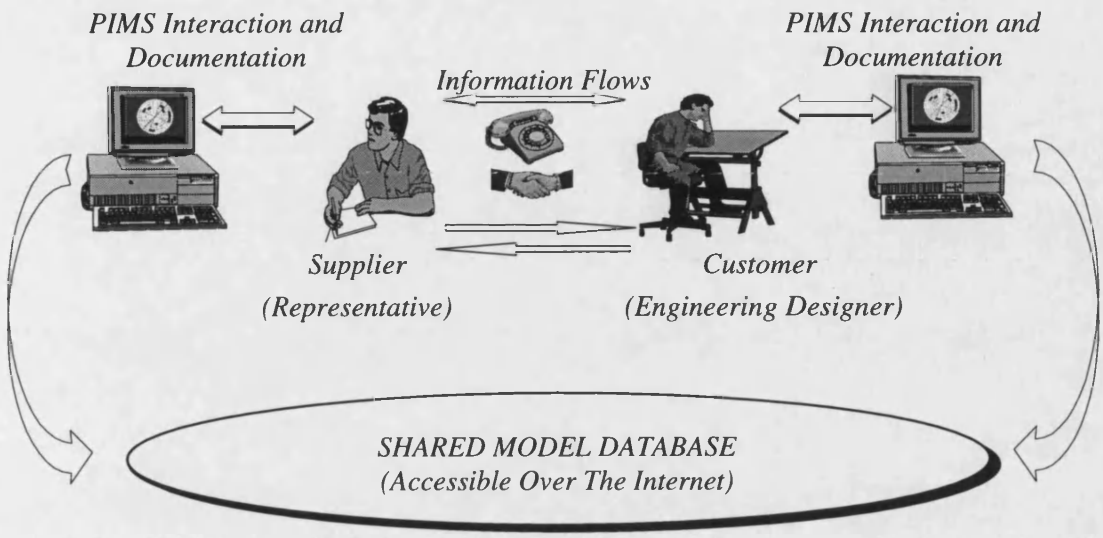

Figure 8.16: An Ideal PIMS Utilisation Scenario

8.4 Overall Conclusions

This research has proved to be successful in the paths taken towards achieving its original aims. It has uncovered many deficiencies in the way that engineering design is currently practised and in so doing identified ways by which they may be overcome. This process that has been aided by and resulted in the development of new tools, techniques, and systems. These have been used to facilitate an enhanced understanding of the issues surrounding the integration of suppliers and their information into the engineering design process. And, of further significance, they have provided an essential platform for future research in the domain of engineering design; a necessity owing to its dynamic nature and the need for continuous improvement in order to accrue competitive advantage in an aggressive global marketplace.

Key Publications

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Appendix 1.
The Meta Classification

This appendix provides details of the Meta classification; a schema that was intended to cover key information types shared between customers and suppliers, and in particular those that impact on the quality of an emerging design.

Development of the Meta Classification

The development of the Meta classification was influenced by various schema found within the domain (Noble, [1989]; Rzevski and Farrar, [1994]; Ullman, [1992b]; Pitts and Maloney, [1977]), together with extracts from ISO 900 and various PDSs obtained from collaborating companies. In the latter case, these detail the demands or constraints that must be achieved by a product, along with further wishes or requirements that should be taken into consideration (Section 2.3.2). Hence, their consideration was believed to be an important aspect in the development of an appropriate classification.

The Meta classification is split into 9 key areas, and within each of these information is classified at a greater level of detail. The information types represented within the classification are believed to be those that impact upon the quality of a design most heavily, and thus in general they should be shared between customers and suppliers during product design and manufacture.

Form	**Fit**	**Process**
Material	How Form Assessed	Capability
Defect Level	How Function Assessed	Tooling
Dimensions	Operating Conditions	Tooling Location
Critical Dimensions	Assembly	
Tolerances	Interfacing Components	
Critical Tolerances		
Function	**Volumes**	**Handling**
Function	Batch Size	Transportation
	Capacity Planning	Storage
		Packaging
Financial	**Liability**	**Time**
Overall Cost	Overall	Transport - Time Slots
Payment Terms	Rejects and Scrap	Delivery Date
		Lead Time

The Meta Classification

Appendix 2.
PIMS Case Design Projects

This appendix provides details of case design projects B to D, that were undertaken, modelled, and subsequently analysed using the Product Information Modelling (PIMS).

Case Design Project B

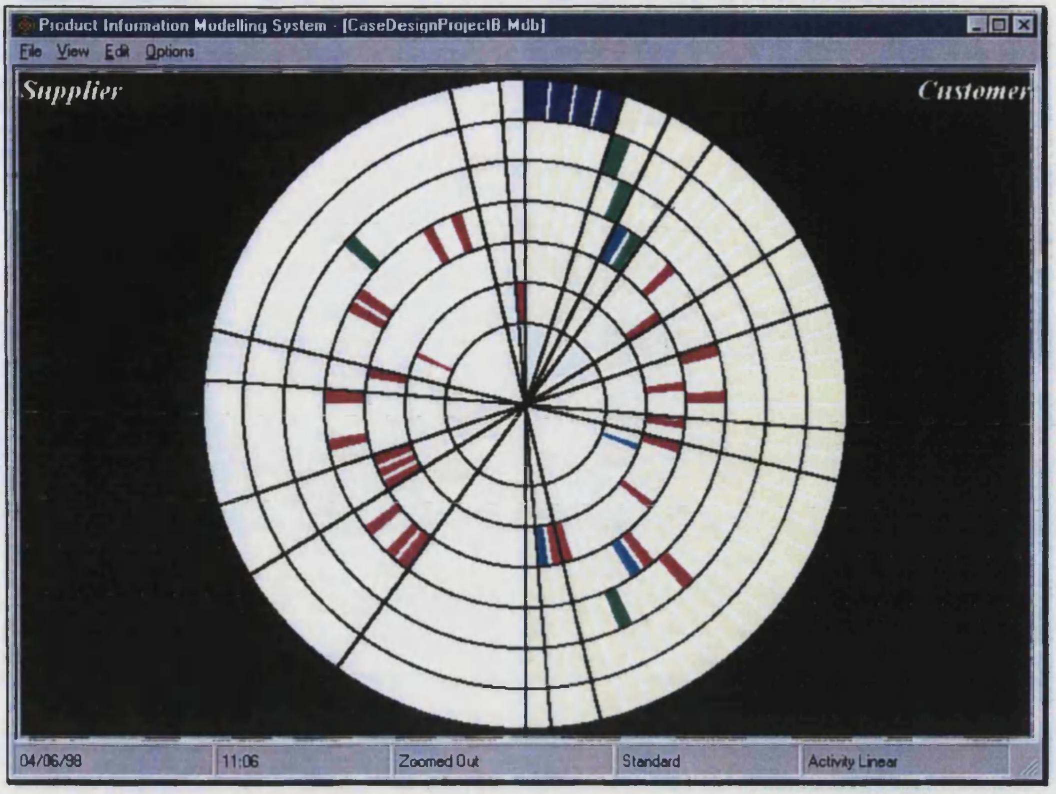
This case design project was concerned with the design of a position adjustable knife edge required to eliminate a 'laser shadow' within a scanner.

- *Design type* - original
- *Volumes* - 25 per year
- *Customer to supplier* - 8 Km

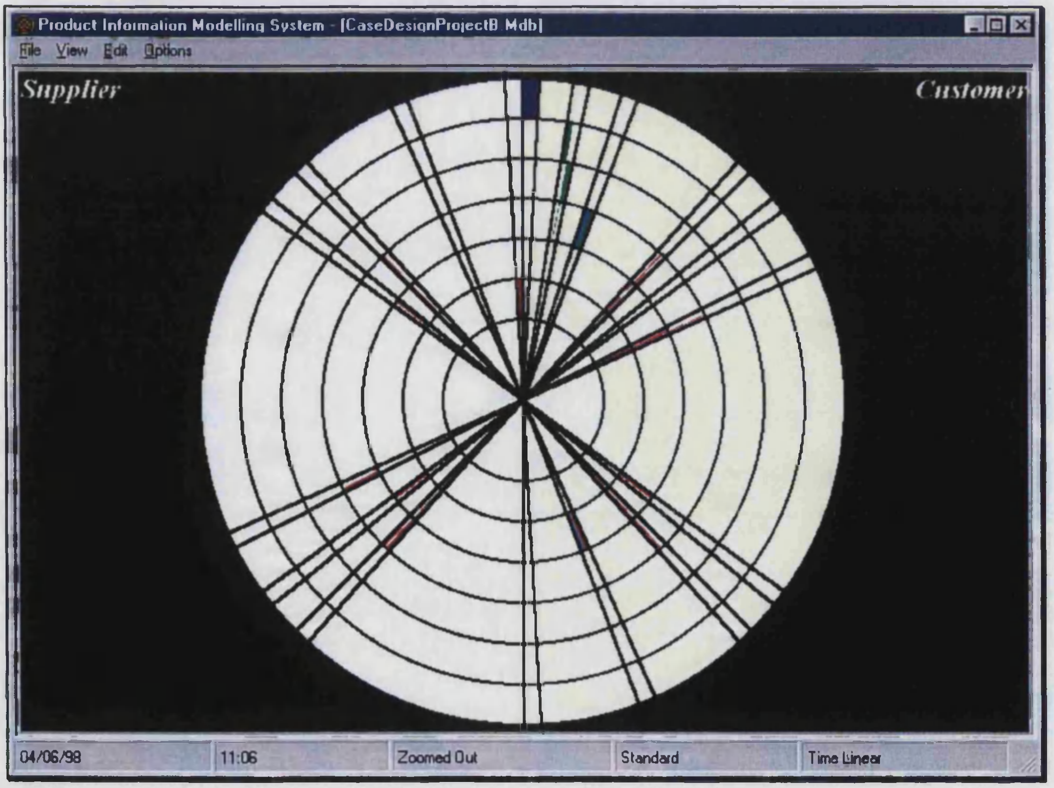
A summary of the information interactions that took place in case design project B are provided in the table that follows. Subsequent figures show a selection of the resultant models, in various display modes, that were produced by PIMS.

No.	Date	Recipient	Origin	Stage	Type	Summary Description
1.01	01/12/95	Customer	Accessed	Need	Request	Requirement for Product
1.02	01/12/95	Customer	Accessed	Need	Function	Design Specification
1.03	01/12/95	Customer	Accessed	Need	Form	Design Specification
1.04	01/12/95	Customer	Accessed	Need	Fitness	Operating Conditions
2.01	04/12/95	Customer	Created	Concept	Form	Design Concept
2.02	04/12/95	Customer	Created	Embodiment	Form	CAD Drawing
3.01	07/12/95	Customer	Extracted	Detail	Form	Design Specification
3.02	07/12/95	Customer	Created	Detail	Form	Finalised Drawings
4.01	15/12/95	Supplier	Customer	Detail	Request	Request Workload
4.02	15/12/95	Supplier	Customer	Detail	Form	Detail Drawings
4.03	15/12/95	Customer	Supplier	Detail	Request	Request Delivery Date
4.04	15/12/95	Supplier	Customer	Detail	Time	Received Delivery Date
4.05	15/12/95	Customer	Supplier	Pre-fabrication	Request	Request Drawings
5.01	18/12/95	Supplier	Customer	Pre-fabrication	Request	Commence Production
5.02	18/12/95	Supplier	Customer	Pre-fabrication	Form	Detail Drawings
5.03	18/12/95	Supplier	Customer	Pre-fabrication	Volumes	Volume Requirements
6.01	22/12/95	Customer	Supplier	Detail	Request	Request Sharpness
6.02	22/12/95	Supplier	Customer	Detail	Form	Sharpness Requirement
6.03	22/12/95	Customer	Supplier	Pre-fabrication	Process	Material Limitations
6.04	22/12/95	Customer	Supplier	Detail	Request	Material Change
6.05	22/12/95	Supplier	Customer	Detail	Form	New Material
7.01	12/01/96	Customer	Supplier	Pre-fabrication	Process	First-off Complete
7.02	12/01/96	Supplier	Customer	Pre-fabrication	Various	Arrange Visit
8.01	15/01/96	Customer	Supplier	Pre-fabrication	Form	Receive First-off
8.02	15/01/96	Customer	Extracted	Test	Fitness	First-off Analysis
8.03	15/01/96	Supplier	Customer	Test	Fitness	Product Failure
8.04	15/01/96	Supplier	Customer	Detail	Form	Failure Reasons
8.05	15/01/96	Supplier	Customer	Detail	Function	Product Function
8.06	15/01/96	Customer	Supplier	Pre-fabrication	Process	Drawing Deficiencies
8.07	15/01/96	Supplier	Created	Embodiment	Form	Design Modification
8.08	15/01/96	Customer	Supplier	Embodiment	Request	Change Request
8.09	15/01/96	Customer	Supplier	Detail	Form	Design Modification
8.10	15/01/96	Customer	Extracted	Detail	Form	Drawing Analysis
8.11	15/01/96	Supplier	Customer	Detail	Form	Product Acceptance
8.12	15/01/96	Customer	Created	Embodiment	Form	Design Modification
8.13	15/01/96	Supplier	Customer	Detail	Form	Design Modification
8.14	15/01/96	Customer	Supplier	Pre-fabrication	Process	Design Acceptance
9.01	22/01/96	Customer	Supplier	Pre-fabrication	Form	Received Parts
9.02	22/01/96	Customer	Extracted	Pre-fabrication	Fitness	Parts Testing
10.01	29/01/96	Supplier	Customer	Test	Fitness	Product Acceptance

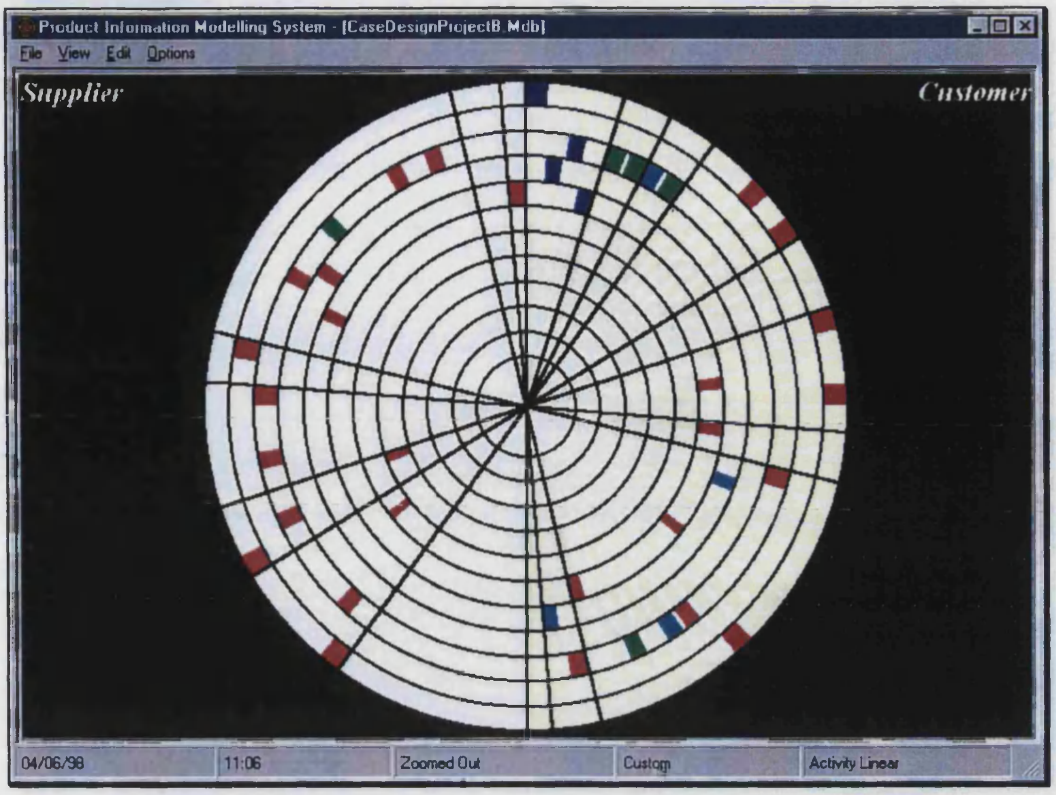
Summary of the Information Interactions in Case Design Project B



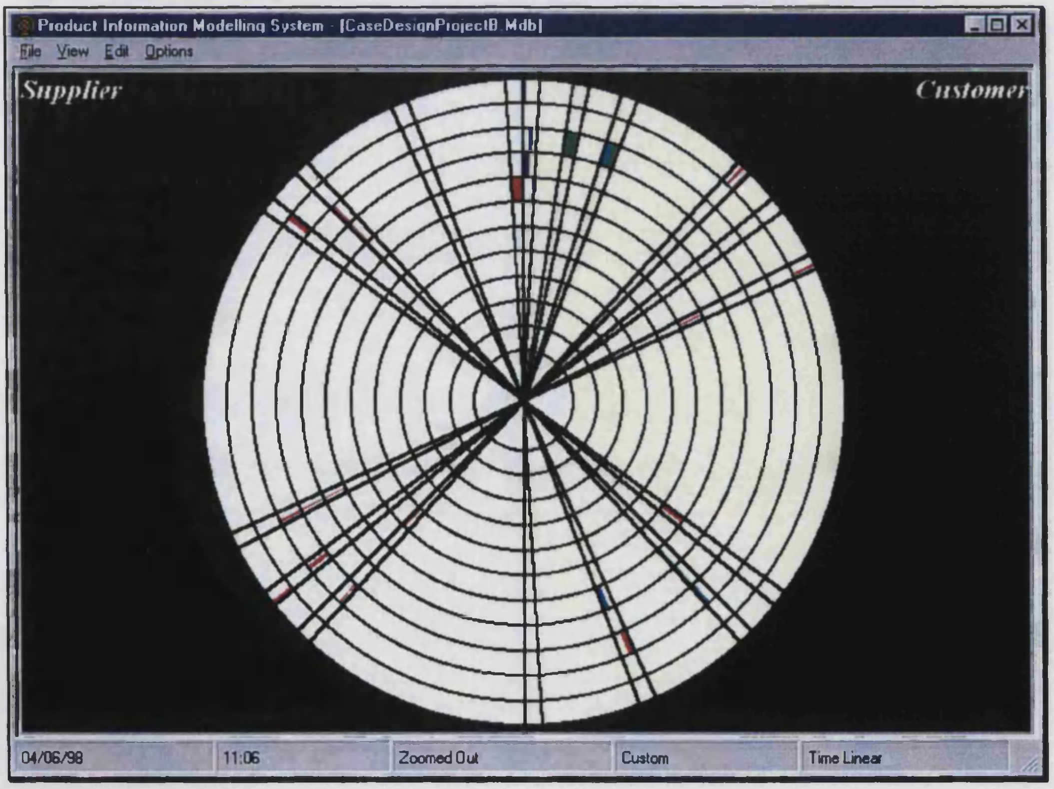
Case Design Project B in Standard Activity Linear Display Mode



Case Design Project B in Standard Time Linear Display Mode



Case Design Project B in Custom Activity Linear Display Mode



Case Design Project B in Custom Activity Linear Display Mode

Case Design Project C

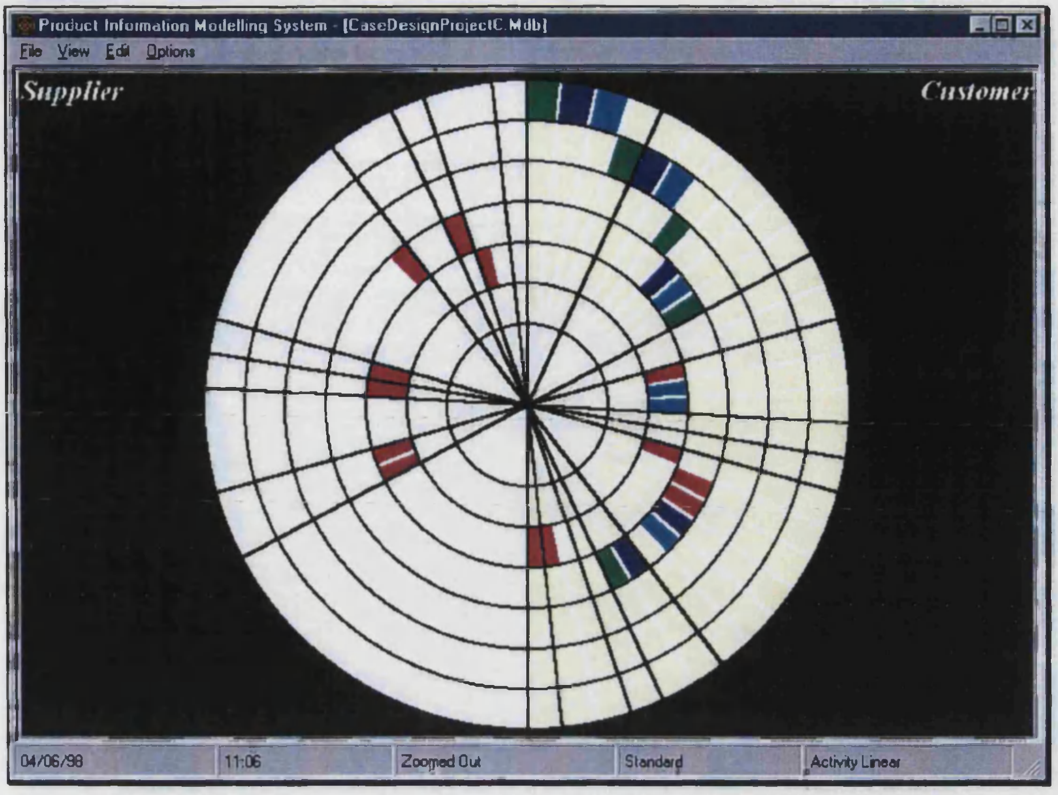
This case design project was concerned with the design of a fixture to enable the testing of a radiator anti-vibration mount.

- *Design type* - variant
- *Volumes* - one off batch of 10
- *Customer to supplier* - 16 Km

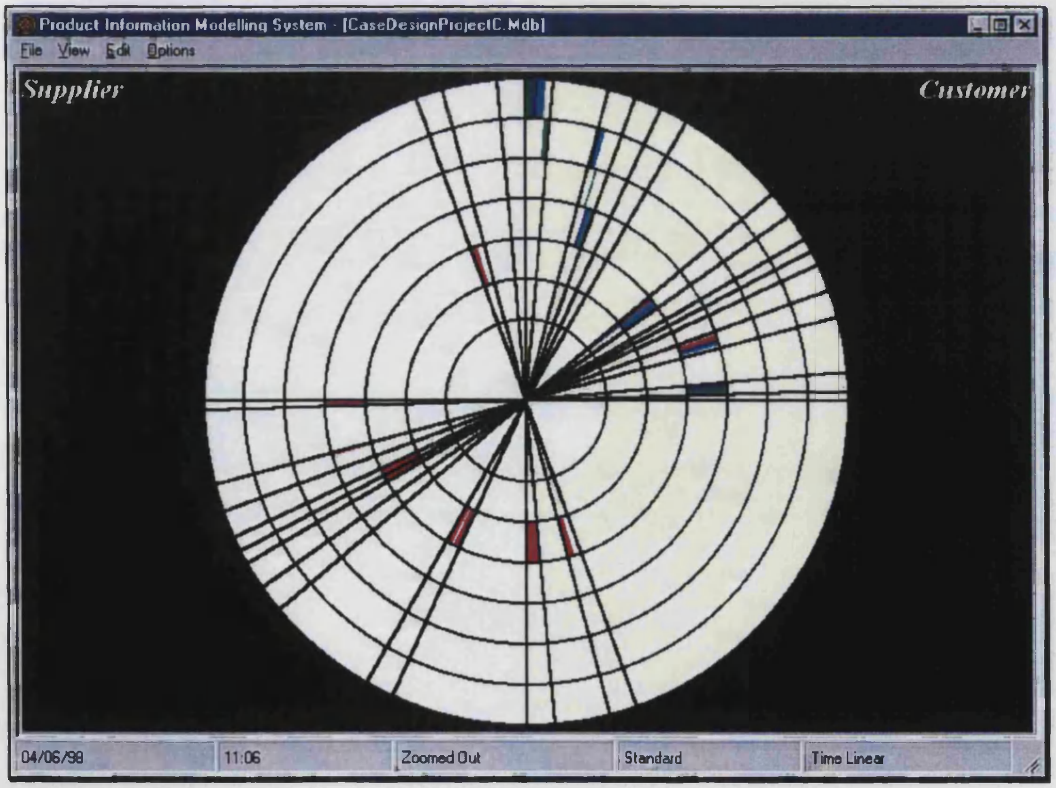
A summary of the information interactions that took place in case design project C are provided in the table that follows. Subsequent figures show a selection of the resultant models, in various display modes, that were produced by PIMS.

No.	Date	Recipient	Origin	Stage	Type	Summary Description
1.01	03/01/97	Customer	Created	Need	Request	Product Requirement
1.02	03/01/97	Customer	Accessed	Need	Various	Design Specification
1.03	03/01/97	Customer	Extracted	Need	Form	Interfacing Components
1.04	03/01/97	Customer	Created	Concept	Form	Concept Design
2.01	06/01/97	Customer	Accessed	Concept	Form	Concept Design
2.02	06/01/97	Customer	Extracted	Concept	Form	Design Analysis
2.03	06/01/97	Customer	Created	Embodiment	Form	CAD Drawing
2.04	06/01/97	Customer	Accessed	Detail	Various	CAD Drawing
2.05	06/01/97	Customer	Extracted	Detail	Various	Analysed Drawing
2.06	06/01/97	Customer	Created	Detail	Various	Finalised Drawing
3.01	08/01/97	Supplier	Customer	Pre-fabrication	Request	Request Quote
3.02	08/01/97	Supplier	Customer	Pre-fabrication	Form	Detail Drawings
4.01	13/01/97	Customer	Supplier	Pre-fabrication	Various	Received Quote
4.02	13/01/97	Customer	Extracted	Pre-fabrication	Request	Cost Analysis
4.03	13/01/97	Customer	Extracted	Pre-fabrication	Time	Delivery Analysis
5.01	15/01/97	Supplier	Customer	Pre-fabrication	Various	Production Request
6.01	15/01/97	Supplier	Customer	Pre-fabrication	Time	Production Confirmation
7.01	17/01/97	Customer	Supplier	Pre-fabrication	Request	Design Modification
7.02	17/01/97	Customer	Supplier	Detail	Form	Stock Levels
7.03	17/01/97	Customer	Supplier	Detail	Time	Time Savings
7.04	17/01/97	Customer	Accessed	Detail	Various	Detail Drawings
7.05	17/01/97	Customer	Extracted	Detail	Form	Drawing Analysis
7.06	17/01/97	Supplier	Customer	Detail	Form	Modification Acceptance
8.01	20/01/97	Customer	Accessed	Detail	Various	Detail Drawings
8.02	20/01/97	Customer	Created	Detail	Form	Drawing Modification
9.01	20/01/97	Supplier	Customer	Detail	Form	Updated Drawing
10.01	04/02/97	Supplier	Customer	Pre-fabrication	Request	Production Query
10.02	04/02/97	Customer	Supplier	Pre-fabrication	Time	Production State
11.01	07/02/97	Customer	Supplier	Pre-fabrication	Form	Received Parts

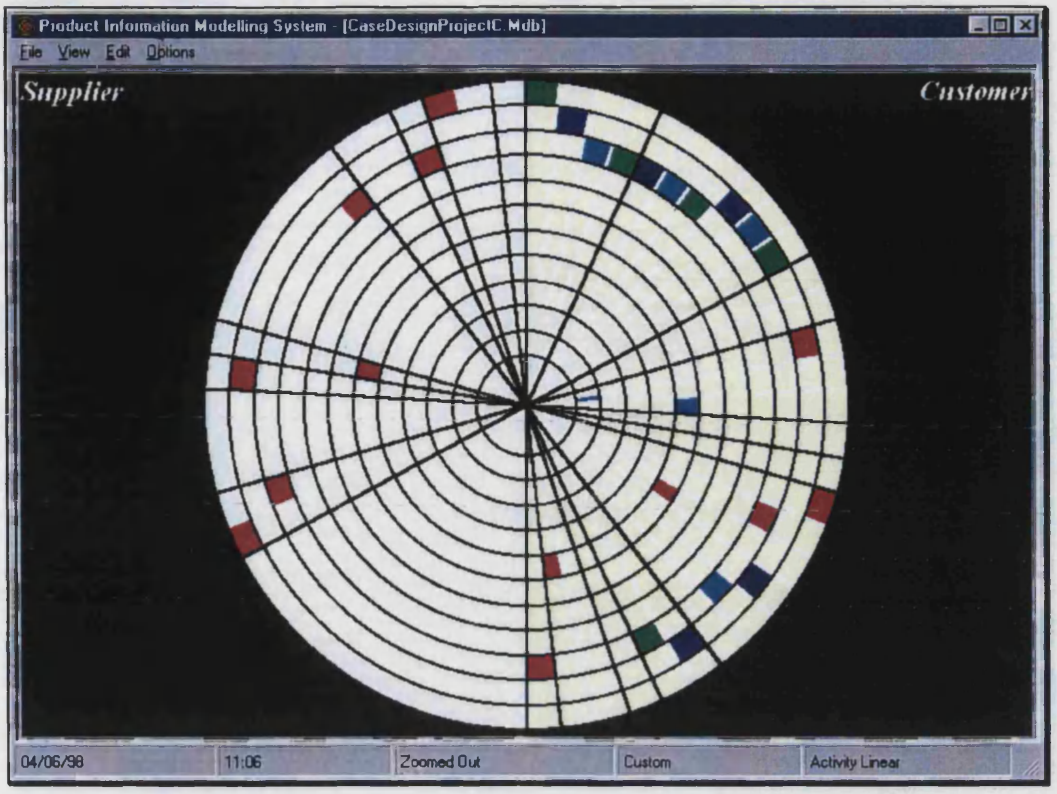
Summary of the Information Interactions in Case Design Project C



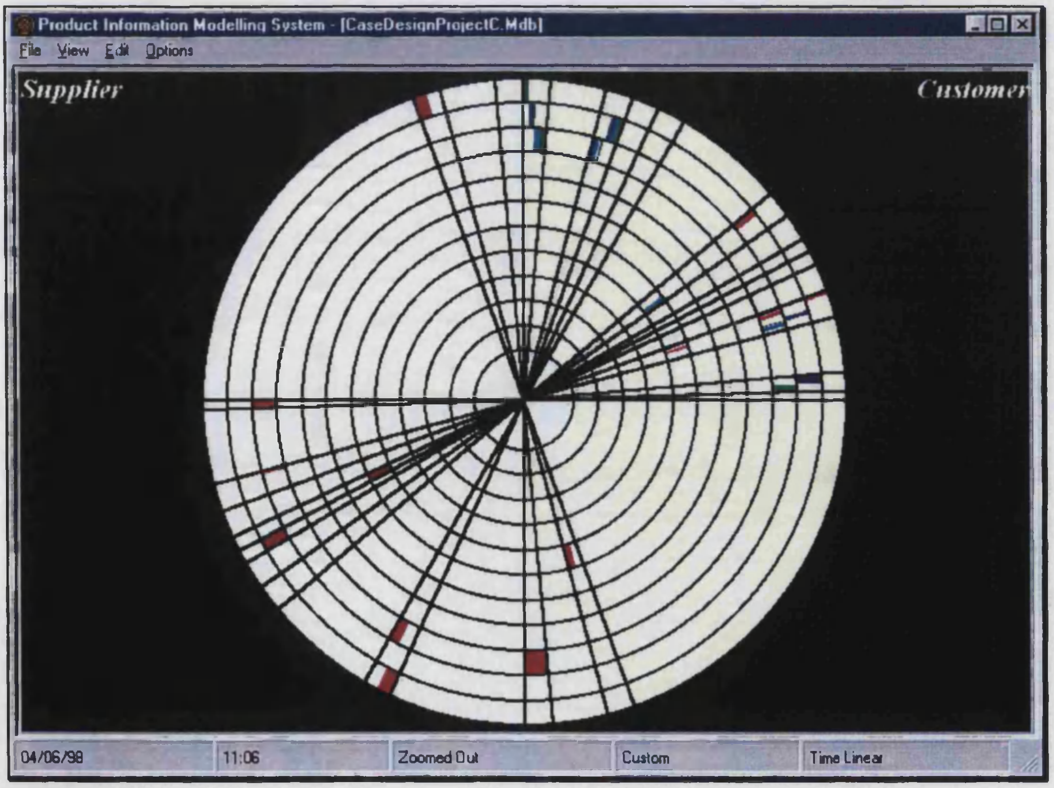
Case Design Project C in Standard Activity Linear Display Mode



Case Design Project C in Standard Time Linear Display Mode



Case Design Project C in Custom Activity Linear Display Mode



Case Design Project C in Custom Time Linear Display Mode

Case Design Project D

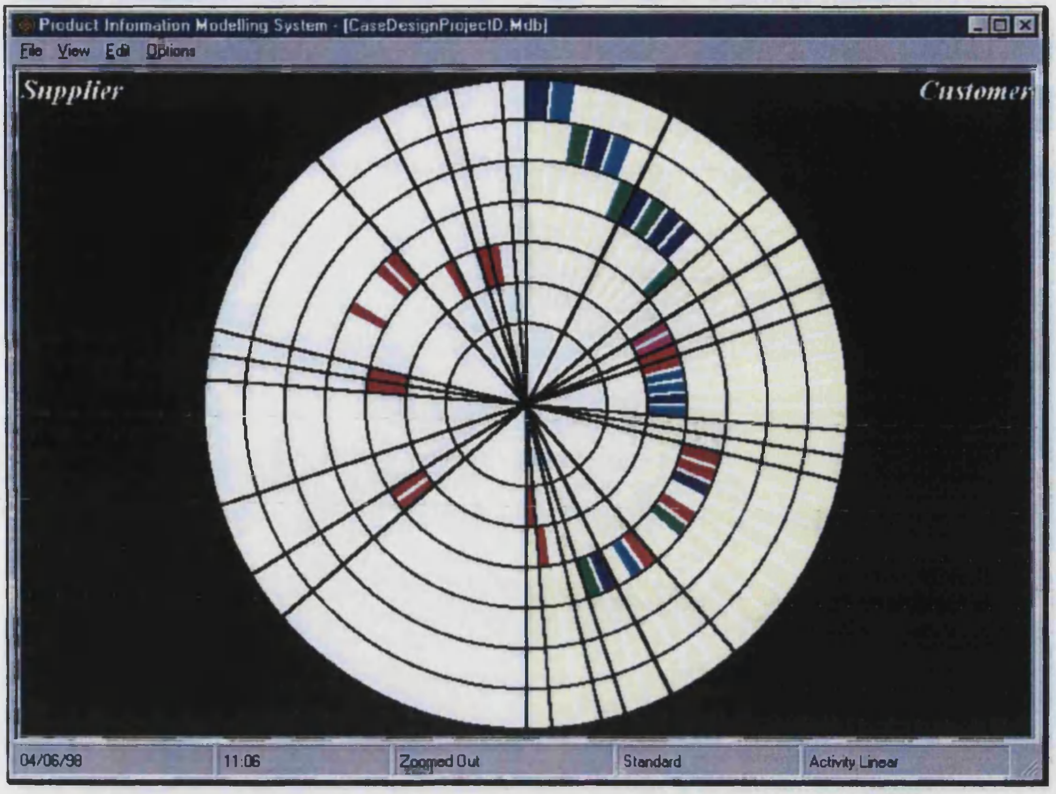
This case design project was concerned with the design of a metal bracket that formed part of a vehicle exhaust mount.

- *Design type* - adaptive
- *Volumes* - initial batch of 25
- *Customer to supplier* - 25 Km

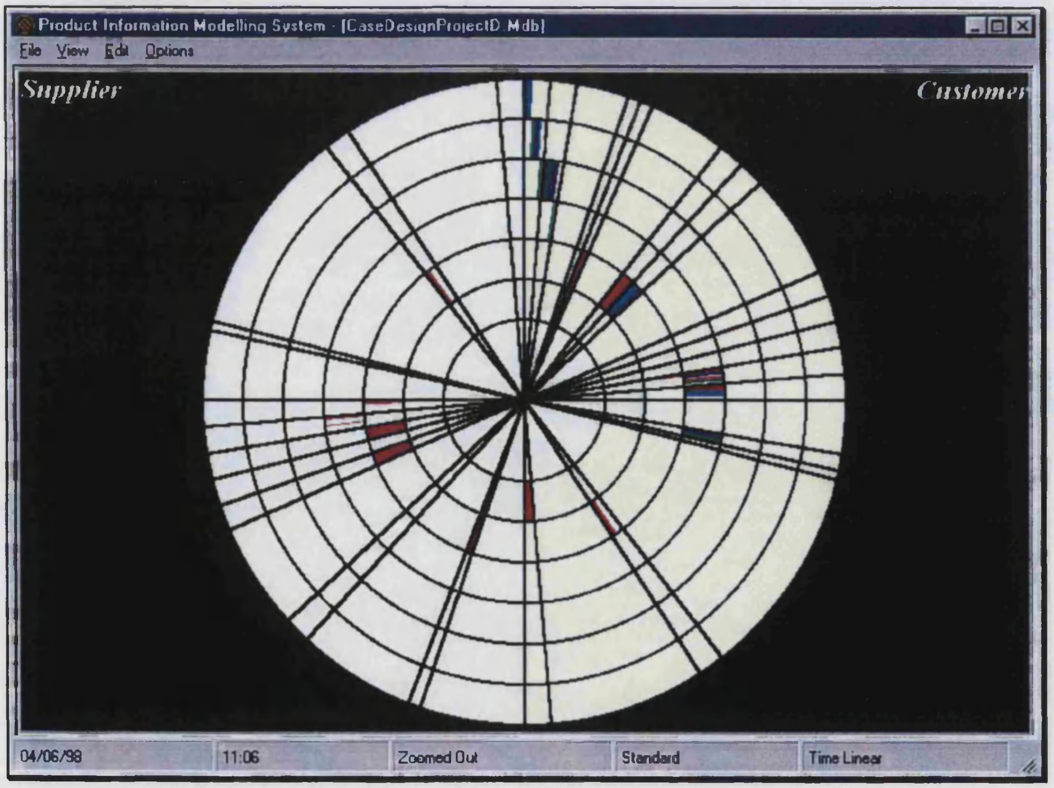
A summary of the information interactions that took place in case design project D are provided in the table that follows. Subsequent figures show a selection of the resultant models, in various display modes, that were produced by PIMS.

No.	Date	Recipient	Origin	Stage	Type	Summary Description
1.01	03/03/97	Customer	Accessed	Need	Various	Design Specification
1.02	03/03/97	Customer	Extracted	Need	Form	Analysed Specification
1.03	03/03/97	Customer	Created	Concept	Form	Concept Design
1.04	03/03/97	Customer	Accessed	Concept	Various	Design Specification
1.05	03/03/97	Customer	Extracted	Concept	Fitness	Operating Conditions
1.06	03/03/97	Customer	Created	Embodiment	Form	Dimensioning
2.01	04/03/97	Customer	Accessed	Embodiment	Various	Design Concept
2.02	04/03/97	Customer	Created	Embodiment	Form	CAD Drawing
2.03	04/03/97	Customer	Accessed	Embodiment	Request	Manufacturing Process
2.04	04/03/97	Customer	Accessed	Embodiment	Process	Acceptable Process
2.05	04/03/97	Customer	Created	Detail	Form	Detail Drawing
3.01	07/03/97	Supplier	Customer	Pre-fabrication	Request	Request Quote
3.02	07/03/97	Supplier	Customer	Pre-fabrication	Form	Detail Drawing
4.01	07/03/97	3rd Party	Customer	Pre-fabrication	Request	Request Quote
4.02	07/03/97	3rd Party	Customer	Pre-fabrication	Form	Detail Drawing
5.01	11/03/97	Customer	3rd Party	Pre-fabrication	Various	Received Quote
6.01	12/03/97	Customer	Supplier	Pre-fabrication	Various	Received Quote
6.02	12/03/97	Customer	Extracted	Pre-fabrication	Time	Deliver Date
6.03	12/03/97	Customer	Extracted	Pre-fabrication	Request	Costing
6.04	12/03/97	Customer	Accessed	Pre-fabrication	Various	Accessed Quote
6.05	12/03/97	Customer	Extracted	Pre-fabrication	Request	Analysed Quote
7.01	17/03/97	Supplier	Customer	Pre-fabrication	Request	Production Request
8.01	19/03/97	Supplier	Customer	Pre-fabrication	Request	Production Confirmation
9.01	18/03/97	Customer	Supplier	Detail	Process	Design Modification
9.02	20/03/97	Customer	Supplier	Detail	Request	Cost Saving
9.03	20/03/97	Customer	Accessed	Detail	Various	Detail Drawings
9.04	20/03/97	Supplier	Customer	Detail	Request	Request Modifications
9.05	20/03/97	Customer	Supplier	Detail	Form	Design Modifications
9.06	20/03/97	Customer	Created	Detail	Form	Design Modification
9.07	20/03/97	Supplier	Customer	Detail	Form	Design Acceptance
9.08	20/03/97	Supplier	Customer	Detail	Request	Request Modifications
10.01	21/03/97	Customer	Supplier	Detail	Form	Modified Drawings
10.02	21/03/97	Customer	Extracted	Detail	Form	Drawing Analysis
10.03	21/03/97	Supplier	Customer	Pre-fabrication	Form	Design Acceptance
11.01	24/03/97	Customer	Accessed	Detail	Various	Detail Drawings
11.02	24/03/97	Customer	Created	Detail	Form	Modified Drawings
12.01	24/03/97	Supplier	Customer	Pre-fabrication	Form	Updated Drawings
13.01	02/04/97	Supplier	Customer	Pre-fabrication	Request	Production Query
13.02	02/04/97	Customer	Supplier	Pre-fabrication	Time	Production Status
14.01	09/04/97	Customer	Supplier	Test	Form	Received Parts

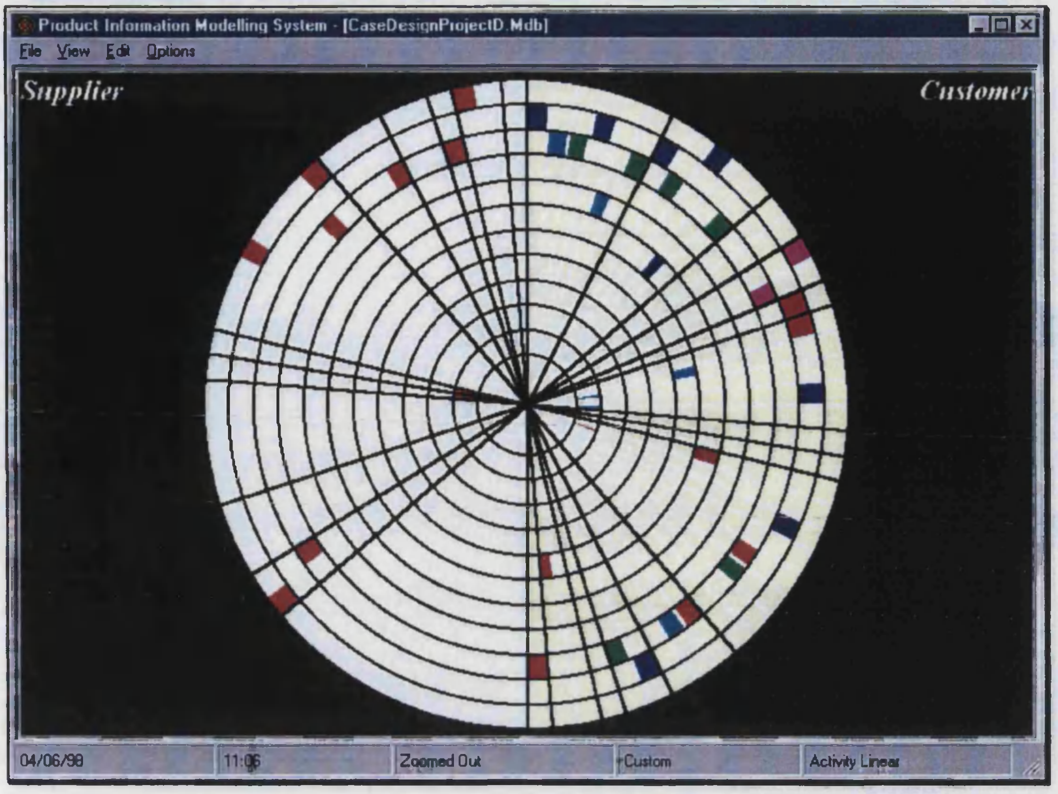
Summary of the Information Interactions in Case Design Project D



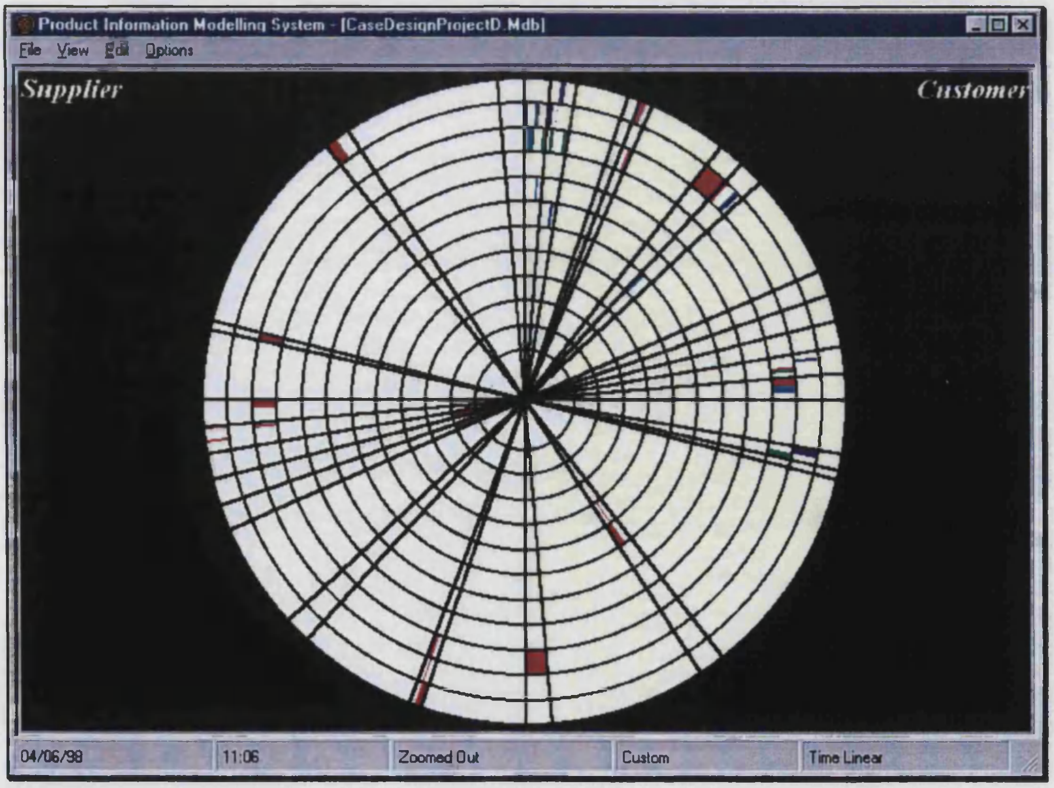
Case Design Project D in Standard Activity Linear Display Mode



Case Design Project D in Standard Time Linear Display Mode



Case Design Project D in Custom Activity Linear Display Mode



Case Design Project D in Custom Time Linear Display Mode

Appendix 3.
The Questionnaire

This appendix provides an example of the questionnaire that was sent out, with help from the Institution of Engineering Designers (IED), to over 1000 engineering designers and managers within the United Kingdom.

THE DEPARTMENT OF MECHANICAL ENGINEERING

UNIVERSITY OF BATH

IN ASSOCIATION WITH

THE INSTITUTION OF ENGINEERING DESIGNERS

An Investigation Into The Information Flows Between Engineering Designers And Suppliers

Funding: Engineering and Physical Sciences Research Council (EPSRC)

Dear Engineer

We would like to ask for your assistance in determining how engineering designers obtain information from and share information with suppliers. Activities that are becoming increasingly important in today's aggressive global market place.

Suppliers are often key sources of information in engineering design, and yet accessing it is often frustrated by the fact that there is either too much available, or a complete absence or even knowledge of what is required, especially in advance of a design project. As a consequence, enormous amounts of time may be spent on the telephone, in meetings, or reading magazines, catalogues, handbooks, etc., to obtain the desired information.

These issues need to be addressed in order to ensure that your design time is used more efficiently and more effective use is made of the information available from suppliers. Your help in completing this questionnaire will be an invaluable step in achieving these aims, and we therefore ask that you do so as soon as it is convenient and forward it to us in the enclosed prepaid envelope.

Thank you for your co-operation in this project. If you would like to receive feedback on the results, please indicate this by ticking the following box: ☐.

Yours faithfully

O.P. Boston : Research Officer, University of Bath.
S.J. Culley : Investigator, University of Bath.
& C.A. McMahon : Investigator, University of Bristol.

This should take approximately 5 to 10 minutes to complete. Please do so by ticking the appropriate box or boxes for each question. Where applicable, information provided in the "Other ...." category would be most appreciated.

1. Which of the following best describes your position in the company ?

☐ Engineering Manager ☐ Project Engineer ☐ Product Engineer ☐ Designer/Draughtsman ☐ Other ___

2. How many years experience in engineering do you have ?

☐ 0-2 ☐ 2-5 ☐ 5-10 ☐ 10-15 ☐ 15-20 ☐ 20-25 ☐ 25+

3. What type of industry is your company involved in ?

☐ Aerospace ☐ Agriculture ☐ Automotive ☐ Construction ☐ Defence ☐ Manufacturing
☐ Oil ☐ Power ☐ Process ☐ Utilities ☐ Other ___

4. How many people does your company employ ?

☐ 0-50 ☐ 50-100 ☐ 100-200 ☐ 200-500 ☐ 500-1000 ☐ 1000+

5. What was your company's turnover last year ?

☐ 0-1£M. ☐ 1-5£M. ☐ 5-10£M. ☐ 10-50£M. ☐ 50-200£M. ☐ 200£M.+

6. What percentage of your design time is spent on the following types of design activity ? (see Note A on page 4)

☐% Original Design ☐% Adaptive Design ☐% Variant Design

7. Which of the following supplier types do you use ?

☐ Partners or Early Involved ☐ Design to Specification ☐ Design and Make to Specification
☐ Make to Drawing ☐ Standard Component ☐ Raw Material

8a. Does your company use a supplier assessment scheme ? ☐ Yes ☐ No (if No, go to question 9).
8b. Does it take into account advice or information obtained from suppliers ? ☐ Yes ☐ No (if No, go to question 9).
8c. Are formal procedures in place within your company for evaluating or grading this ? ☐ Yes ☐ No.

9a. Does your company have a list of approved suppliers ? ☐ Yes ☐ No (if No, go to question 10).
9b. Is this list readily available to engineers within the engineering department ? ☐ Yes ☐ No.
9c. Does it explicitly state what type of service suppliers are approved for ? ☐ Yes ☐ No.

10. Is the decision regarding the level of supplier involvement in a design project (e.g. involving a supplier at the concept phase of the design process) **aided by any formal guidelines ? ☐ Yes ☐ No.**

11a. Are supplier catalogues or other forms of standard supplier literature (such as handbooks) **used within your company ? ☐ Yes ☐ No** (if No, go to question 12).
11b. Do you have a personal collection of them ? ☐ Yes ☐ No.
11c. Are they also stored within a "library" accessible to engineers ? ☐ Yes ☐ No (if No, go to question 12).
11d. How is this material indexed within the library ?

☐ Not Indexed ☐ Material Format ☐ Supplier Name ☐ Catalogue Name
☐ Design Area ☐ Design Project ☐ Importance ☐ Other ___

11e. Do formal guidelines exist for the management of this material (e.g. updating or discarding it) **? ☐ Yes ☐ No.**
11f. Do you use electronic supplier catalogues ? ☐ Yes ☐ No.

12. Do you have access to any of the following computing facilities whilst at work ?

☐ Own Computer ☐ Office Computer ☐ Central Computer ☐ No Access
☐ The World Wide Web ☐ e-mail ☐ Video Conferencing ☐ Speech Recognition System

13a. Information may be obtained directly from suppliers via many different types of communication media. In order that we may establish popularity, please indicate for each medium how many times during a typical working week you obtain supplier information via that medium ?

		Letters	Fax	E-mail	Telephone	In Person	Other......
0	Never	☐	☐	☐	☐	☐	☐
0-5	Rarely	☐	☐	☐	☐	☐	☐
5-15	Occasionally	☐	☐	☐	☐	☐	☐
15-25	Frequently	☐	☐	☐	☐	☐	☐
25+	Always	☐	☐	☐	☐	☐	☐

13b. Please indicate, for each communication medium, how often you store supplier information ?

	Letters	Fax	E-mail	Telephone	In Person	Other
Never	☐	☐	☐	☐	☐	☐
Rarely	☐	☐	☐	☐	☐	☐
Occasionally	☐	☐	☐	☐	☐	☐
Frequently	☐	☐	☐	☐	☐	☐
Always	☐	☐	☐	☐	☐	☐

13c. Please indicate, for each communication medium, where you usually store supplier information ?

	Letters	Fax	E-mail	Telephone	In Person	Other
Diary	☐	☐	☐	☐	☐	☐
Log Book	☐	☐	☐	☐	☐	☐
Project File	☐	☐	☐	☐	☐	☐
Supplier File	☐	☐	☐	☐	☐	☐
Memo	☐	☐	☐	☐	☐	☐
Electronically	☐	☐	☐	☐	☐	☐
Other__	☐	☐	☐	☐	☐	☐

13d. Please indicate, for each communication medium, how often you share supplier information with other engineers within your department ?

	Letters	Fax	E-mail	Telephone	In Person	Other
Never	☐	☐	☐	☐	☐	☐
Rarely	☐	☐	☐	☐	☐	☐
Occasionally	☐	☐	☐	☐	☐	☐
Frequently	☐	☐	☐	☐	☐	☐
Always	☐	☐	☐	☐	☐	☐

14. Do you keep comprehensive records of what information has been provided to and obtained from suppliers during a design project ? ☐ Yes ☐ No.

15. Please indicate the potential value of a tool or technique that would enable you to predict what information might be required for a design project before starting it ?

☐ Very Valuable ☐ Fairly Valuable ☐ Valuable ☐ Negligible Value ☐ No Value

16a. Do formal guidelines exist within your company on what information should be shared with suppliers during a design project ? ☐ Yes ☐ No.

16b. Do formal guidelines exist within your company on what information should not be shared with suppliers during a design project ? ☐ Yes ☐ No.

17. If suppliers had access to more information about the design project being undertaken within your company, what effect do you think that this would have on the quality of the design ?

☐ Very Good ☐ Fairly Good ☐ Negligible ☐ Poor ☐ Very Poor

18a. Does your company have an official design process ? ☐ Yes ☐ No (if No, go to question 19).

18b. Does it explicitly take into account communications with suppliers ? ☐ Yes ☐ No (if No, go to question 19).

18c. Please indicate how valuable you find it when dealing with suppliers ?

☐ Very Valuable ☐ Fairly Valuable ☐ Valuable ☐ Negligible Value ☐ No Value

19. How good are links and relationships between the engineering and purchasing departments in your company ?

☐ Very Good ☐ Fairly Good ☐ Good ☐ Poor ☐ Very Poor

20. Please indicate if you have ever received any formal training in relation to either of the following ?

☐ Information Classification ☐ Information Storage ☐ Information Retrieval

☐ Presenting Information ☐ Communicating Information ☐ Decision Making

21. Please indicate using a scale of 5 to 1, for the following sources of information, how valuable you have found them in the past for making you aware of either: new products, new materials, new processes, or technology advancements in general; 5 being very valuable and 1 being no value ?

☐ Talking to Colleagues ☐ Talking to Suppliers ☐ Talking to Reps. ☐ Supplier Literature ☐ Exhibitions

☐ Trade Magazines ☐ Technical Journals ☐ Conferences ☐ Magazines in General ☐ Television

☐ World Wide Web ☐ Newspapers ☐ Competitors Products ☐ Products in General ☐ Other.......

It would be most appreciated if you could provide the names of yourself and your company. These will be kept in strictest confidence and they will not be referred to in any subsequent publication.

Your Name .... Company Name ....

Please tick the following box if you would be prepared to discuss, in brief, certain aspects of this questionnaire: ☐.

You are welcome to make any further constructive comments should you feel these would be useful......

Thank you for completing this questionnaire. Please return it in the prepaid envelope provided.

Note A: The percentage time spent on each of the following activities should add up to 100%:

Original Design which involves elaborating an original solution principle for a system (plant, machine or assembly) with the same, a similar, or new task.

Adaptive Design which involves adapting a known system (the solution principle remaining the same) to a changed task. Here the original designs of parts or assemblies are often called for.

Variant Design which involves varying the size and/or arrangement of certain aspects of the chosen system, the function and solution principle remaining unchanged.